NOAA Technical Memorandum NESDIS NGDC-46

DIGITAL ELEVATION MODELS OF SANTA MONICA, CALIFORNIA: PROCEDURES, DATA SOURCES AND ANALYSIS

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National Geophysical Data Center
Marine Geology and Geophysics Division
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NOTICE

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Also available from the National Technical Information Service (NTIS)
(http://www.ntis.gov)

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1. Introduction

In March of 2010, the National Geophysical Data Center (NGDC), an office of the National Oceanic and Atmospheric Administration (NOAA), developed two bathymetric–topographic digital elevation models (DEMs) of Santa Monica, California (Fig. 1). A 1/3 arc-second[1] DEM referenced to North American Vertical Datum of 1988 (NAVD 88) was carefully developed and evaluated. An NAVD 88 to mean high water (MHW) 1/3 arc-second conversion grid was then created to represent the relationship between NAVD 88 and MHW in the Santa Monica region. A 1/3 arc-second MHW DEM, combining the NAVD 88 DEM and the conversion grid, will be used as input for the Method of Splitting Tsunami (MOST) model developed by the Pacific Marine Environmental Laboratory (PMEL) NOAA Center for Tsunami Research (http://nctr.pmel.noaa.gov/) to simulate tsunami generation, propagation and inundation. The NAVD 88 DEM was generated from diverse digital datasets in the region (grid boundary and sources shown in Fig. 5). The MHW DEM will be used for tsunami inundation modeling, as part of the tsunami forecast system Short-term Inundation Forecasting for Tsunamis (SIFT) currently being developed by PMEL for the NOAA Tsunami Warning Centers. This report provides a summary of the data sources and methodology used in developing both Santa Monica DEMs.

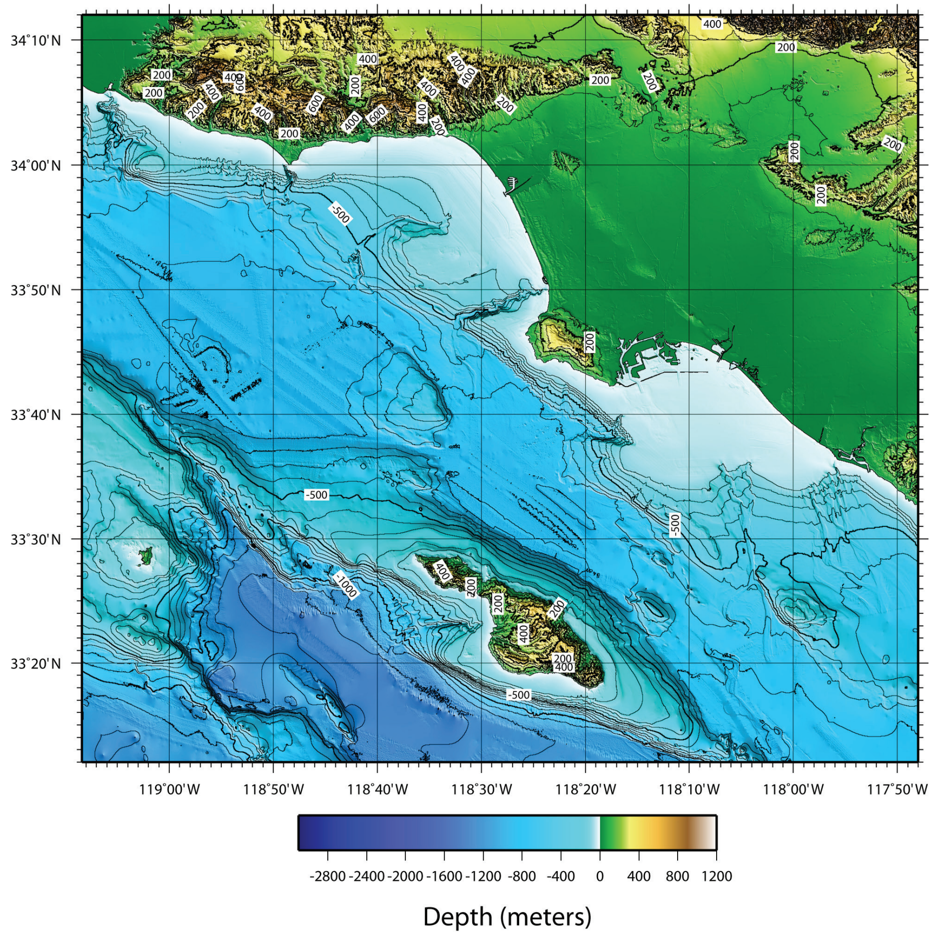

Figure 1. Shaded-relief image of the Santa Monica NAVD 88 1/3 arc-second DEM. Contour interval is 100 meters. Image is in Mercator projection.

1. The Santa Monica DEMs are built upon a grid of cells that are square in geographic coordinates (latitiude and longitude), however, the cells are not square when converted to projected coordinate systems such as UTM zones (in meters). At the latitude of Santa Monica, California, (34°01' 19"N, 118°28'53"W) 1/3 arc-second of latitude is equivalent to 10.27 meters; 1/3 arc-second of longitude equals 8.55 meters.

2. Study Area

Santa Monica is located in western Los Angeles County on the southern coast of California between Point Mugu to the north and Newport Beach to the south (Fig. 2). The DEM also encompasses the communities of Malibu, Marina del Rey, Redondo Beach, Los Angeles, Long Beach, and Huntington Beach. The city is known as one of the leading sustainable cities in the United States with a focus on environmentally-friendly practices and reduction of greenhouse gas emissions. The city is situated on a generally flat slope with high bluffs along the coast in northern parts of the city. After significant population growth during the early and mid-20th century, the population has been nearly steady since the 1960s. The population estimate from the Census Bureau in 2008 was approximately 87,000.

Located in an historically active earthquake region, the North and South Branches of the Santa Monica Fault run roughly southwest to northeast across the western half of the city. Plate movement creates a highly active region at risk for earthquakes and associated hazards, such as landslides and tsunamis (Fig. 3). In addition, the entire region surrounding Santa Monica contains a significant number of faults, including the San Andreas Fault to the north (Fig. 4).

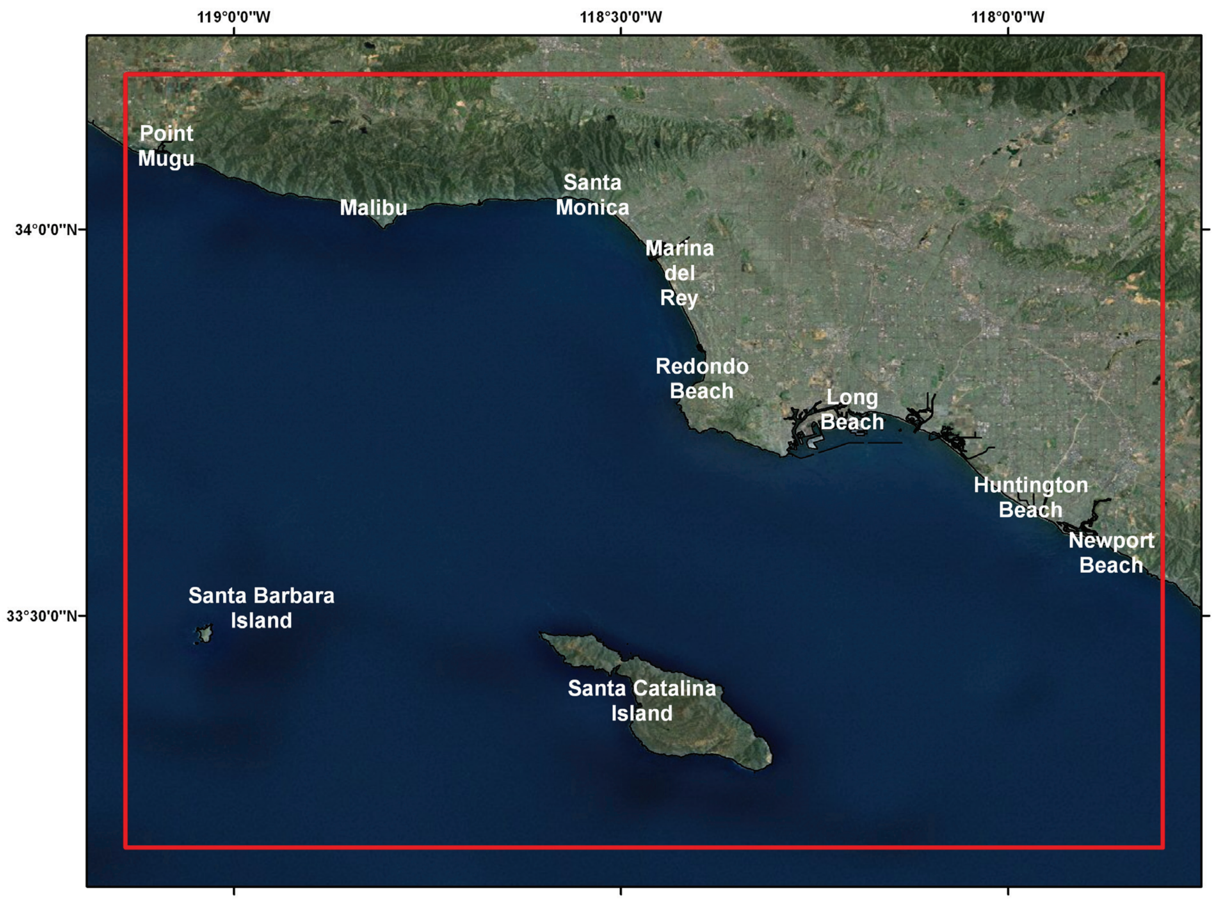

Figure 2. Overview of the Santa Monica DEM region. ESRI World 2D imagery is in the background. Red box denotes DEM boundary.

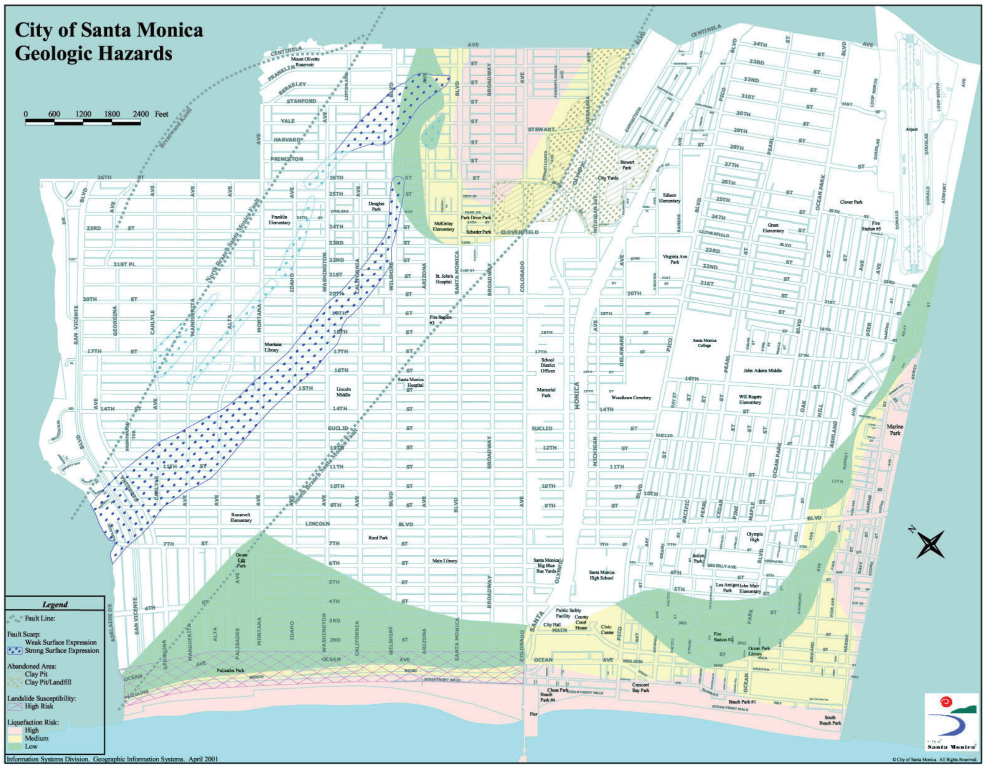

Figure 3. City of Santa Monica geologic hazards map. Dashed black lines indicate fault lines. Source: http://www.smgov.net/isd/gis/

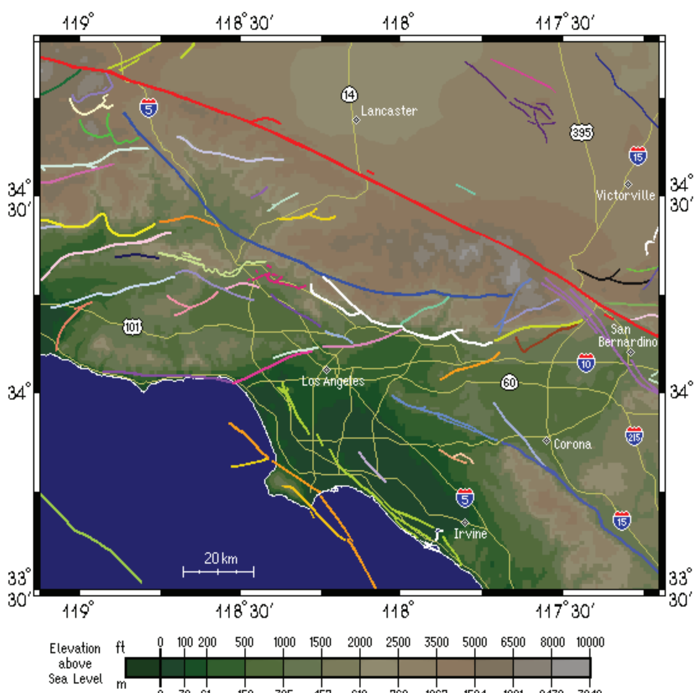

Figure 4. Fault lines in the Santa Monica region. San Andreas Fault shown in red. Other fault types shown in varying colors. Blind thrust faults are not indicated. Source: Southern California Earthquake Data Center (http://www.data.scec.org/faults/lafault.html)

3. Methodology

The Santa Monica NAVD 88 and MHW DEMs were constructed to meet PMEL specifications (Table 1), based on input requirements for the development of Reference Inundation Models (RIMs) and Standby Inundation Models (SIMs) (*V. Titov, pers. comm.*) in support of NOAA's Tsunami Warning Centers use of SIFT to provide real-time tsunami forecasts in an operational environment. The best available bathymetric and topographic digital data were obtained by NGDC and shifted to common horizontal and vertical datums: North American Datum of 1983[2] (NAD 83) and NAVD 88. The resulting NAVD 88 DEM was then shifted to MHW using a conversion grid for modeling of maximum flooding. Data were gathered in an area slightly larger (~5%) than the DEM extents. This data "buffer" ensures that gridding occurs across rather than along the DEM boundaries to prevent edge effects. Data processing and evaluation, and DEM assembly and assessment are described in the following subsections.

Table 1a. Specifications for the Santa Monica NAVD 88 DEM.

Grid Area	Santa Monica, California
Coverage Area	119.14º to 117.80º W; 33.20º to 34.20º N
Coordinate System	Geographic decimal degrees
Horizontal Datum	World Geodetic System of 1984 (WGS 84)
Vertical Datum	North American Vertical Datum of 1988 (NAVD 88)
Vertical Units	Meters
Cell Size	1/3 arc-second
Grid Format	ESRI Arc ASCII raster grid

Table 1b. PMEL specifications for the Santa Monica MHW DEM.

Grid Area	Santa Monica, California
Coverage Area	119.14º to 117.80º W; 33.20º to 34.20º N
Coordinate System	Geographic decimal degrees
Horizontal Datum	World Geodetic System of 1984 (WGS 84)
Vertical Datum	Mean high water (MHW)
Vertical Units	Meters
Cell Size	1/3 arc-second
Grid Format	ESRI Arc ASCII raster grid

2.The horizontal difference between the North American Datum of 1983 (NAD 83) and World Geodetic System of 1984 (WGS 84) geographic horizontal datums is approximately one meter across the contiguous U.S., which is significantly less than the cell size of the DEMs. Most GIS applications treat the two datums as identical, so do not actually transform data between them, and the error introduced by not converting between the datums is insignificant for our purposes. NAD 83 is restricted to North America, while WGS 84 is a global datum. As tsunamis may originate most anywhere around the world, tsunami modelers require a global datum, such as WGS 84 geographic, for their DEMs so that they can model the wave's passage across ocean basins. These DEMs are identified as having a WGS 84 geographic horizontal datum even though the underlying elevation data were typically transformed to NAD 83 geographic. At the scale of the DEMs, WGS 84 and NAD 83 geographic are identical and may be used interchangeably.

3.1 Data Sources and Processing

Shoreline, bathymetric, and topographic digital datasets (Fig. 5) were obtained from several U.S. federal, state and local agencies, and academic institutions including: NGDC; NOAA's National Ocean Service (NOS), Office of Coast Survey (OCS) and Coastal Services Center (CSC); the California Department of Fish and Game (CDFG); the California State University Seafloor Mapping Laboratory (CSUMB); the U.S. Army Corps of Engineers (USACE); and the U.S. Geological Survey (USGS). Safe Software's *FME* data translation tool package was used to shift datasets to NAD 83 geographic horizontal datum and to convert them into ESRI *ArcGIS* shapefiles[3]. The shapefiles were then displayed with *ArcGIS* and Applied Imagery's *Quick Terrain Modeler* (*QT Modeler*) to assess data quality and manually edit datasets. Vertical datum transformations to NAVD 88 were accomplished using NOAA's *Vertical Datum* (*VDatum*) transformation tool. ESRI's online *World 2D* imagery was used to analyze and modify data. *QT Modeler* and Interactive Visualization System's *Fledermaus* software were used to evaluate processing and gridding techniques.

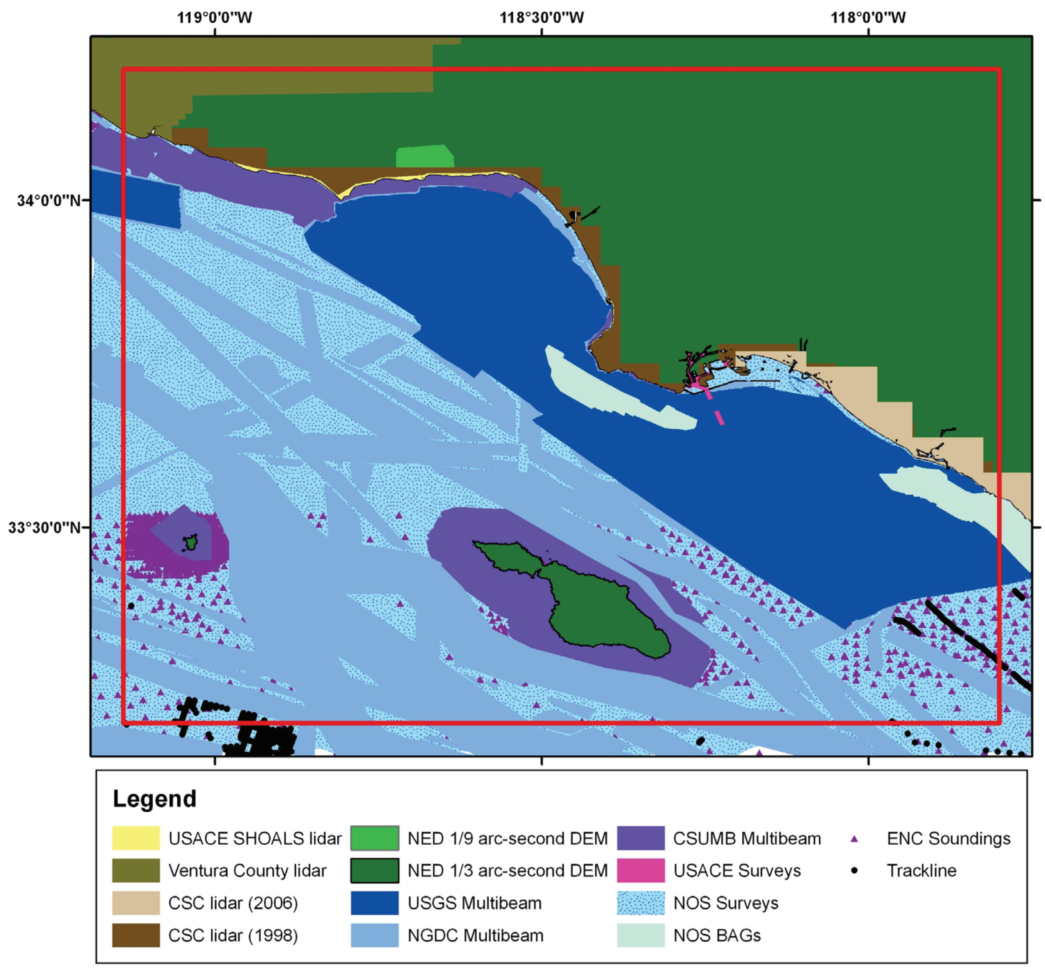

Figure 5. Source and coverage of datasets used in compiling the Santa Monica NAVD 88 DEM. Red box denotes DEM boundary.

3. *FME* uses the North American Datum Conversion Utility (NADCON; http://www.ngs.noaa.gov/TOOLS/Nadcon/Nadcon.shtml) developed by NOAA's National Geodetic Survey (NGS) to convert data from NAD 27 to NAD 83. NADCON is the U.S. Federal Standard for NAD 27 to NAD 83 datum transformations.

3.1.1 Shoreline

Coastline datasets of the Santa Monica region were obtained from NOAA's OCS as Electronic Navigational Charts (ENCs)[4] and from CDFG's Marine Region GIS Unit (Table 2; Fig. 6). These two datasets were used to develop a "combined coastline" of the Santa Monica region.

Table 2. Shoreline datasets used in developing the Santa Monica NAVD 88 DEM.

Source	*Year*	*Data Type*	*Spatial Resolution*	*Original Horizontal Datum/ Coordinate System*	*Original Vertical Datum*	*URL*
OCS	2009	ENC	1:20,000	WGS 84 geographic	MHW	http://www.nauticalcharts.noaa.gov/mcd/enc/index.htm
CDFG	1996	Digitized 1:24,000 USGS quads	1:24,000	NAD 83 geographic	Mean high tide	http://www.dfg.ca.gov/bio-geodata/

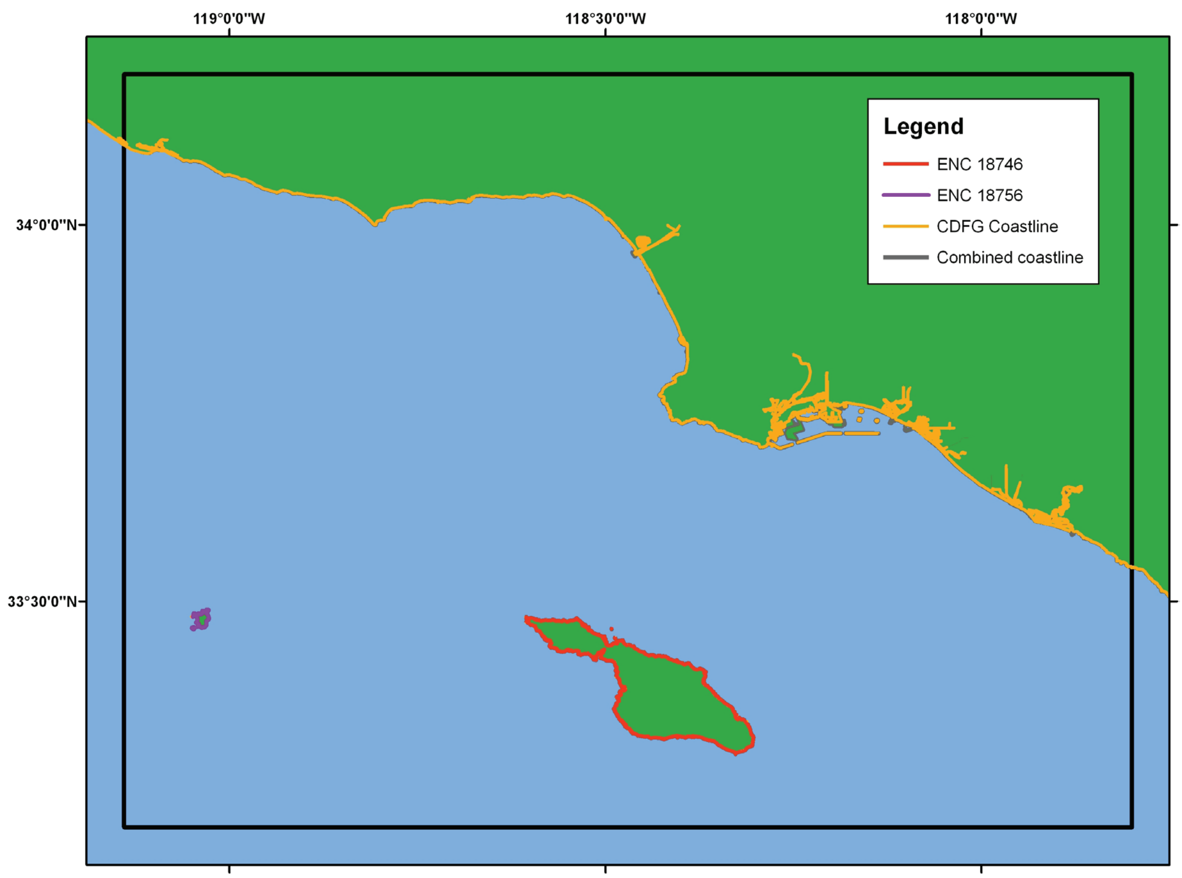

Figure 6. Digital coastline datasets used in developing a combined coastline of the Santa Monica region. Water areas shown in blue. Land areas shown in green. Black box denotes DEM boundary.

4. The Office of Coast Survey (OCS) produces NOAA Electronic Navigational Charts (NOAA ENC®) to support the marine transportation infrastructure and coastal management. NOAA ENC®s are in the International Hydrographic Office (IHO) S-57 international exchange format, comply with the IHO ENC Product Specification and are provided with incremental updates, which supply Notice to Mariners corrections and other critical changes. NOAA ENC®s are available for free download on the OCS web site. [Extracted from NOAA OCS web site: http://www.nauticalcharts.noaa.gov/mcd/enc/index.htm]

1) Office of Coast Survey extracted Electronic Navigational Chart coastlines

Nine ENCs were available for the Santa Monica area (Table 3) and were downloaded from NOAA's Office of Coast Survey web site (http://www.nauticalcharts.noaa.gov/mcd/enc/index.htm). The ENCs are in S-57 format and include coastline data referenced to MHW. The coastline shapefiles were extracted from the ENCs using *ArcCatalog* and compared to large-scale RNCs and ESRI's *World 2D* imagery. Only the 1:20,000-scale ENCs #18746 and #18756 coastlines were used for the offshore islands of Santa Catalina and Santa Barbara, respectively.

Table 3. Electronic and raster nautical charts available in the Santa Monica region.

Chart	*Title*	*Edition*	*Issue Data*	*Type*	*Scale*
18720	Point Dume to Purisima Point	33rd	2009	ENC/RNC	1:232,188
18724	Port Hueneme	2nd	2009	RNC	1:20,000 and 1:12,500
18725	Port Hueneme to Santa Barbara	29th	2009	ENC/RNC	1:50,000; 1:20,000; and, 1:12,500
18740	San Diego to Santa Rosa Island	12th	2009	ENC	1:234,270
18744	Santa Monica Bay	32nd	2009	RNC	1:40,000 and 1:10,000
18746	San Pedro Channel	37th	2009	ENC/RNC	1:80,000 and 1:20,000
18748	El Segundo and Approaches	1st	2009	RNC	1:15,000
18749	San Pedro Bay	42th	2009	ENC/RNC	1:20,000 and 1:15,000
18751	Los Angeles and Long Beach Harbors	46th	2009	ENC/RNC	1:12,000
18756	Santa Barbara Island	8th	2009	ENC/RNC	1:20,000
18757	Santa Catalina Island	11th	2009	RNC	1:40,000 and 1:10,000
18762	San Clemente Island	15th	2009	ENC/RNC	1:40,000
18763	San Clemente Island Northern Part	10th	2009	RNC	1:20,000 and 1:5,000
18764	San Clemente Island Pyramid Cove and Approaches	3rd	2007	ENC	1:15,000
18774	Gulf of Santa Catalina	11th	2009	RNC	1:100,000 and 1:15,000

2) California Department of Fish and Game vector shoreline

The CDFG coastline was originally developed by the California State Land Commission from digitized USGS 7.5' quadrangles to define the mean high tide line and was subsequently rebuilt to reduce tolerances by the CDFG in 1996. The coastline was downloaded from the CDFG web site (see Table 2).

The extracted ENC coastlines were merged with the CDFG coastline using *ArcCatalog* and used to create a combined coastline of the Santa Monica region. The combined coastline was modified to include large offshore rocks and small islets shown on the larger-scale RNCs and clipped to 0.05 degrees larger than the DEM boundary. Smaller piers and docks were deleted from the coastline. The coastline was further modified based on *World 2D* imagery to reflect the most current coastal morphology. The large wharves in the region surrounding Los Angeles and Long Beach Harbors are supported by 3 to 4 foot diameter concrete pilings spaced at approximate intervals of 10 to 15 feet. Due to their expected strength, NGDC included the wharves in the combined coastline and the DEMs. The wharves were digitized by NGDC using *World 2D* imagery as a reference (Fig. 7).

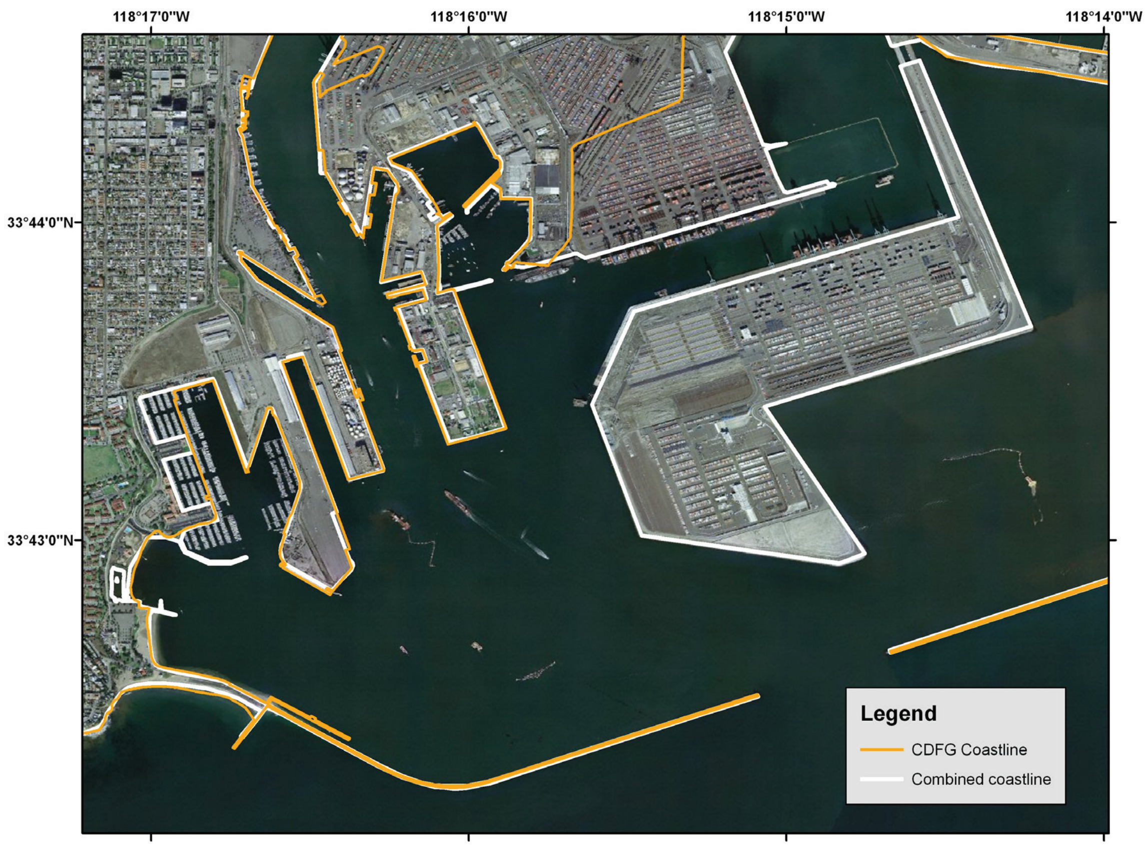

Figure 7. Coastlines in the vicinity of Los Angeles and Long Beach Harbors. ESRI World 2D imagery (shown in background) was used to digitize a representative coastline, which included a recently built wharf and several breakwaters.

In addition, a second coastline that did not contain the wharves in Los Angeles and Long Beach Harbors was developed for assistance in creating a bathymetric surface (see Section 3.3.2). Figure 8 shows this "adjusted coastline" in the region where changes to the "combined coastline" were made. To ensure steep transitions of elevations from the seafloor to the surface of the wharves, the adjusted coastline was used to create a continous bathymetric surface in the harbors, before clipping to the combined coastline. An xyz file of the adjusted coastline with points every 10 meters was generated using NGDC's *GEODAS* software for use in creating the 'pre-surface' bathymetric grid.

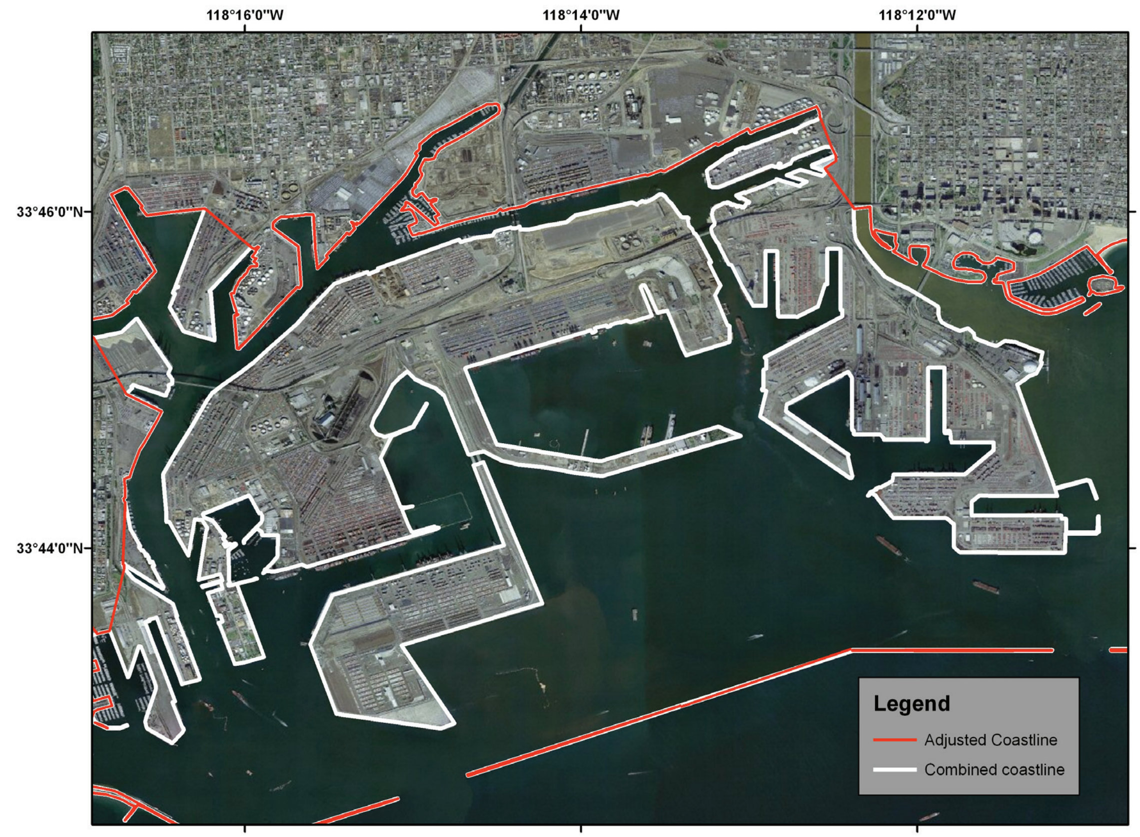

Figure 8. Adjusted and combined coastlines in the region surrounding Los Angeles and Long Beach Harbors. ESRI World 2D imagery is shown in the background.

3.1.2 Bathymetry

Bathymetric datasets available for use in the compilation of the Santa Monica DEMs include 92 NOS hydrographic surveys; 26 multibeam surveys downloaded from the NGDC multibeam database; hydrographic surveys from USACE; multibeam surveys from CSUMB; and soundings extracted from several ENCs (Table 4; Fig. 9).

Table 4. Bathymetric datasets used in compiling the Santa Monica NAVD 88 DEM.

Source	*Year*	*Data Type*	*Spatial Resolution*	*Downloaded Horizontal Datum/ Coordinate System*	*Original Vertical Datum*	*URL*
NGDC	1932 to 2008	NOS hydrographic survey soundings	Ranges from less than 10 m to 600 m (varies with scale of survey, depth, traffic, and probability of obstructions)	NAD 83 geographic	MLLW	http://www.ngdc.noaa.gov/mgg/bathymetry/hydro.html
NGDC	1992 to 2006	Multibeam swath sonar	Gridded to 1 arc-second	WGS 84 geographic	Assumed Mean Sea Level	http://www.ngdc.noaa.gov/mgg/bathymetry/multibeam.html
USACE	2007	Hydrographic survey	Ranges from 1 to 3 meters	NAD 83 California State Plane V (meters and feet)	MLLW	http://www.spl.usace.army.mil/cms/index.php
CSUMB	2001 to 2008	Multibeam swath sonar	1 meter grid	WGS 84 UTM 10 North	NAVD 88	http://seafloor.csumb.edu/index.html
OCS	1977 to 2009	ENC extracted soundings	Ranges from several meters to several kilometers (varies with scale of survey, depth, traffic, and probability of obstructions)	WGS 84 geographic	MLLW	http://www.nautical-charts.noaa.gov/mcd/enc/index.htm

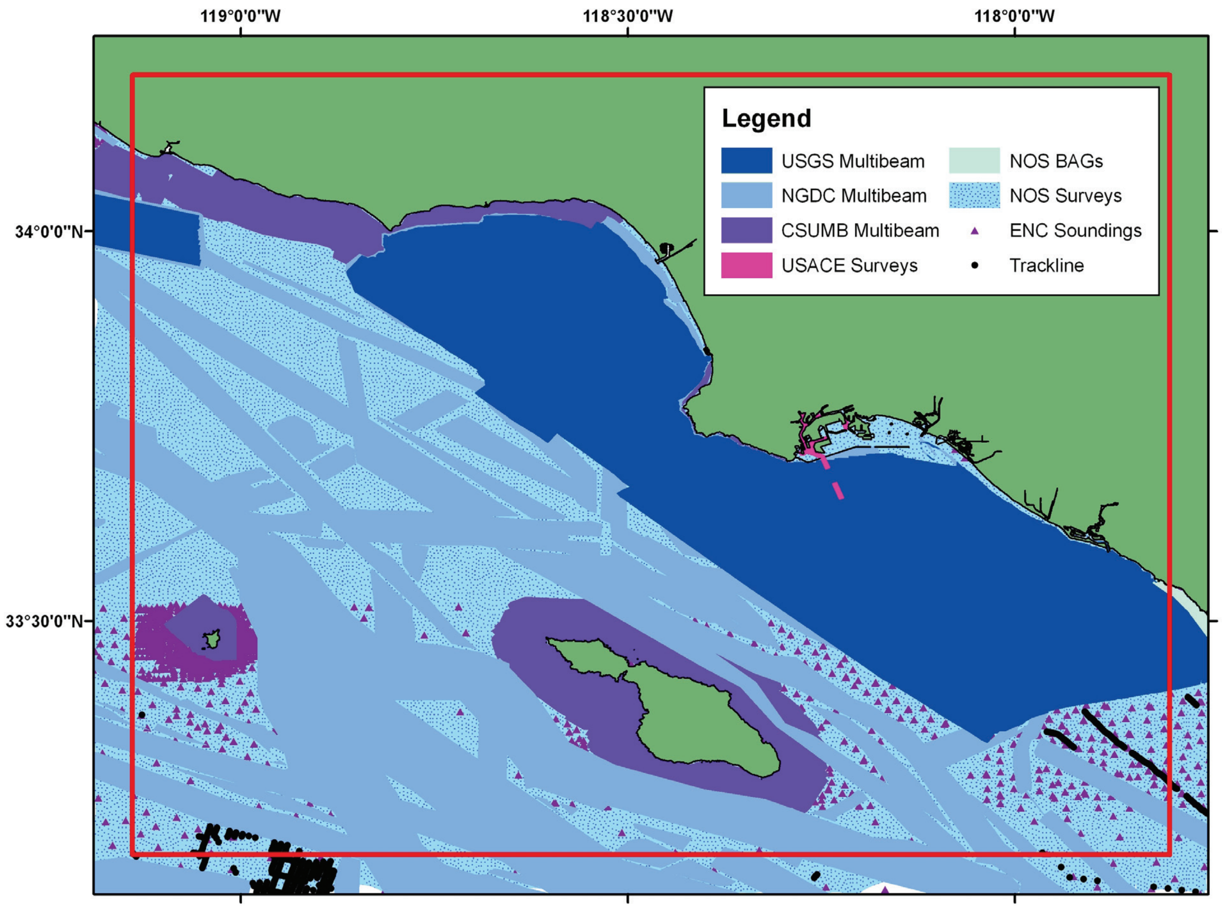

Figure 9. Source and coverage of bathymetric datasets used in compiling the Santa Monica NAVD 88 DEM. Red box denotes DEM boundary.

1) National Ocean Service hydrographic survey data

A total of 92 NOS hydrographic surveys conducted between 1932 and 2008 were available for use in developing the Santa Monica DEMs. Surveys were extracted from NGDC's online NOS hydrographic database using *GEODAS*[5]. The downloaded hydrographic survey data were vertically referenced to mean lower low water (MLLW) and horizontally referenced to NAD 83 geographic. Only 61 of the 92 surveys were used in building the Santa Monica DEM, as several older surveys have been superseded by newer or higher resolution surveys (Table 5; Fig. 10).

Data point spacing for the NOS surveys varied by scale. In general, small scale surveys had greater point spacing than large scale surveys. The data were converted to shapefiles using *FME* software, an integrated collection of spatial extract, transform, and load tools for data transformation (http://www.safe.com/). The surveys were subsequently clipped to a polygon 0.05 degree (~5%) larger than the Santa Monica DEM area to support data interpolation along grid edges.

After converting all NOS survey data to NAVD 88 using the *VDatum* transformation tool (see Sec. 3.2.1), the data were displayed in ESRI *ArcMap* and reviewed for digitizing errors against scanned original survey smooth sheets and edited as necessary. The surveys were also compared to other bathymetric datasets, the combined coastline, and NOS raster nautical charts (RNCs). Older surveys were clipped to remove soundings that have been superseded by more recent NOS surveys, USACE surveys, and multibeam data.

5. *GEODAS* uses the North American Datum Conversion Utility (NADCON; http://www.ngs.noaa.gov/TOOLS/Nadcon/Nadcon.shtml) developed by NOAA's National Geodetic Survey (NGS) to convert hydrographic survey data from NAD 27 to NAD 83. NADCON is the U.S. Federal Standard for NAD 27 to NAD 83 datum transformations.

Table 5. Digital NOS hydrographic surveys used in compiling the Santa Monica NAVD 88 DEM.

NOS Survey ID	*Year of Survey*	*Survey Scale*	*Original Horizontal Datum*	*Original Vertical Datum*
H05235	1933	10,000	NAD 27	MLLW
H05305*	1932	10,000	NAD 27	MLLW
H05306*	1932	40,000	NAD 27	MLLW
H05363	1933	10,000	NAD 27	MLLW
H05364	1933	10,000	NAD 27	MLLW
H05390	1933	10,000	NAD 27	MLLW
H05391	1933	10,000	NAD 27	MLLW
H05392	1933	10,000	NAD 27	MLLW
H05396	1933	10,000	NAD 27	MLLW
H05397	1933	10,000	NAD 27	MLLW
H05425	1933	10,000	NAD 27	MLLW
H05426	1933	10,000	NAD 27	MLLW
H05429	1934	5,000	NAD 27	MLLW
H05446*	1934	40,000	NAD 27	MLLW
H05485	1933	10,000	NAD 27	MLLW
H05486	1935	10,000	NAD 27	MLLW
H05487	1934	10,000	NAD 27	MLLW
H05507*	1934	40,000	NAD 27	MLLW
H05523	1934	20,000	NAD 27	MLLW
H05524	1934	20,000	NAD 27	MLLW
H05532	1934	10,000	NAD 27	MLLW
H05533	1935	10,000	NAD 27	MLLW
H05534	1934	20,000	NAD 27	MLLW
H05555*	1934	20,000	NAD 27	MLLW
H05556*	1934	10,000	NAD 27	MLLW
H05557*	1934	5,000	NAD 27	MLLW
H05558*	1934	5,000	NAD 27	MLLW
H05600	1934	20,000	NAD 27	MLLW
H05602*	1934	10,000	NAD 27	MLLW
H05603*	1934	10,000	NAD 27	MLLW
H05646	1933	40,000	NAD 27	MLLW
H05653	1935	40,000	NAD 27	MLLW
H05658*	1934	20,000	NAD 27	MLLW
H05848*	1934	40,000	NAD 27	MLLW
H05851*	1935	80,000	NAD 27	MLLW
H06115*	1935	40,000	NAD 27	MLLW
H06116*	1935	40,000	NAD 27	MLLW
H06118*	1937	80,000	NAD 27	MLLW
H06259*	1937	80,000	NAD 27	MLLW
H06260*	1937	80,000	NAD 27	MLLW
H06261*	1937	20,000	NAD 27	MLLW
H08921	1968	10,000	NAD 27	MLLW
H09114*	1970	40,000	NAD 27	MLLW
H09253*	1972	40,000	NAD 27	MLLW
H09277*	1972	40,000	NAD 27	MLLW
H09468*	1974	10,000	NAD 27	MLLW
H09469*	1974	10,000	NAD 27	MLLW

NOS Survey ID	Year of Survey	Survey Scale	Original Horizontal Datum	Original Vertical Datum
H09470*	1974	5,000	NAD 27	MLLW
H09471*	1974-1977	5,000	NAD 27	MLLW
H09487*	1974-1975	10,000	NAD 27	MLLW
H09492*	1975	10,000	NAD 27	MLLW
H09493*	1975	10,000	NAD 27	MLLW
H09494	1975	20,000	NAD 27	MLLW
H09495*	1975	5,000	NAD 27	MLLW
H09496*	1975	5,000	NAD 27	MLLW
H09497*	1975	5,000	NAD 27	MLLW
H09498*	1975	20,000	NAD 27	MLLW
H09499*	1975	20,000	NAD 27	MLLW
H09508*	1975	20,000	NAD 27	MLLW
H09558*	1975	10,000	NAD 27	MLLW
H09559*	1975	10,000	NAD 27	MLLW
H09560*	1975	10,000	NAD 27	MLLW
H09561	1975	20,000	NAD 27	MLLW
H09570*	1975	5,000	NAD 27	MLLW
H09575*	1975-1976	10,000	NAD 27	MLLW
H09576	1975	20,000	NAD 27	MLLW
H09580*	1975	10,000	NAD 27	MLLW
H09590	1976-1977	10,000	NAD 27	MLLW
H09591*	1976	10,000	NAD 27	MLLW
H09592*	1976	5,000	NAD 27	MLLW
H09598	1976	10,000	NAD 27	MLLW
H09599*	1976-1977	10,000	NAD 27	MLLW
H09600	1976	10,000	NAD 27	MLLW
H09667*	1976	20,000	NAD 27	MLLW
H09670*	1977-1978	5,000	NAD 27	MLLW
H09671*	1977-1978	5,000	NAD 27	MLLW
H09672*	1977-1978	5,000	NAD 27	MLLW
H09673*	1977-1978	5,000	NAD 27	MLLW
H09674*	1977	5,000	NAD 27	MLLW
H09725	1977	20,000	NAD 27	MLLW
H10331	1990	10,000	NAD 83	MLLW
H10997*	2000	5,000	NAD 83	MLLW
H10998*	2000	10,000	NAD 83	MLLW
H11024*	2001	10,000	NAD 83	MLLW
H11471[a]	2005	5,000	NAD 83	MLLW
H11501[a]	2005	5,000	NAD 83	MLLW
H11879[b]	2008	N/A	NAD 83	MLLW
H11880[a]	2008	N/A	NAD 83	MLLW
H11881[a]	2008	N/A	NAD 83	MLLW
H11882[a]	2008	N/A	NAD 83	MLLW
H11883[b]	2008	N/A	NAD 83	MLLW
H11891[b]	2008	N/A	NAD 83	MLLW

* Denotes NOS surveys used in compiling the Santa Monica DEMs.
[a] Denotes NOS survey available in bathymetric attributed grid (BAG) format.
[b] Denotes NOS survey downloaded from CSUMB.

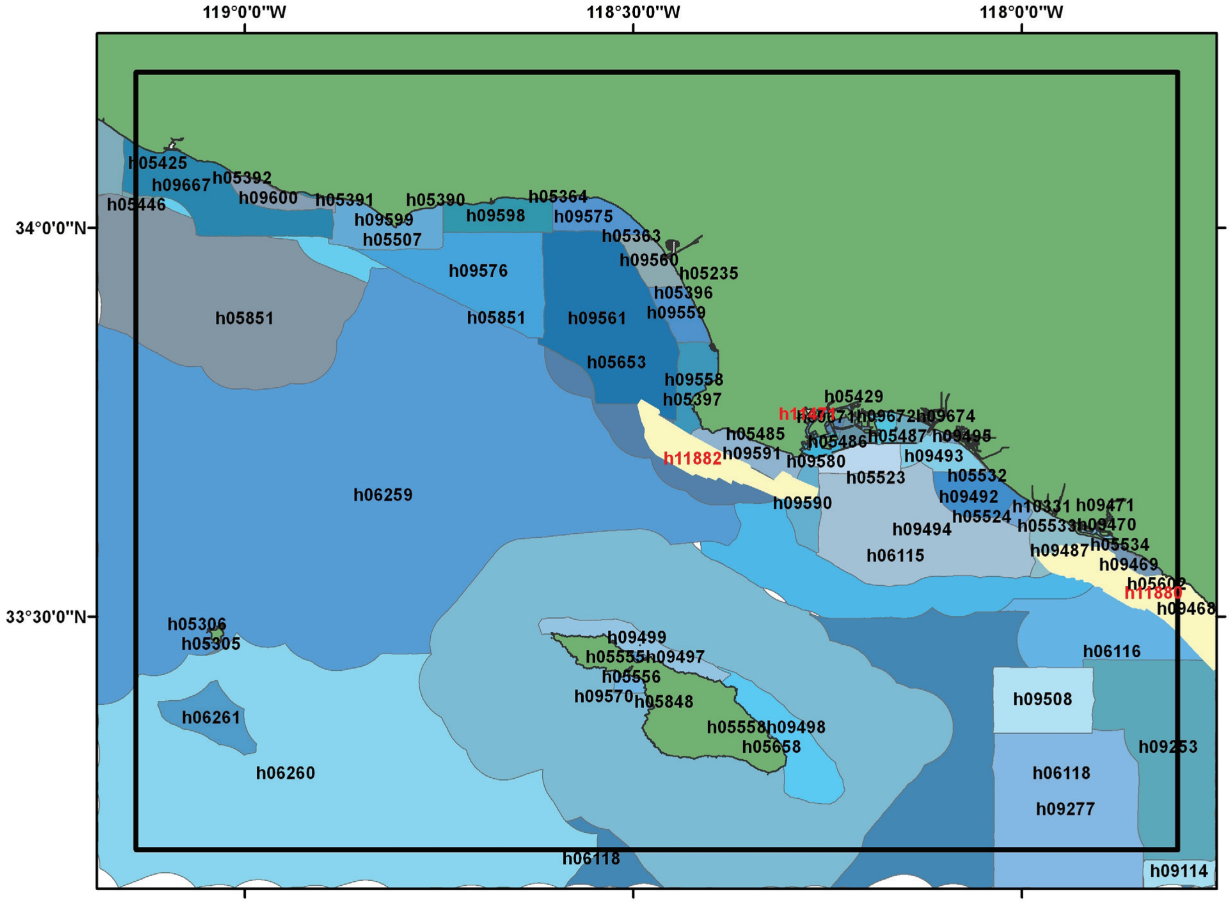

Figure 10. Digital NOS hydrographic survey coverage in the Santa Monica region. Several older surveys were not used as they have been superseded by more recent surveys. Black box denotes DEM boundary. NOS BAG files shaded in yellow with red text; coastline is in grey.

2) NGDC multibeam swath sonar surveys

Twenty-six multibeam swath sonar surveys were available from the NGDC multibeam bathymetry database (Table 6). The data were referenced to WGS 84 geographic horizontal datum and were assumed to be in MSL vertical datum. The data were gridded to extents approximately 5 percent larger than the DEM extents using *MB-System*[6] (http://www.ldeo.columbia.edu/res/pi/MB-System/) at 1 arc-second and viewed in *QT Modeler* for quality analysis. Editing was done using *QT Modeler* and *ArcMap* to eliminate errors where survey data overlapped. The grid was then converted to xyz format and the elevations were transformed from MSL to NAVD 88 using *VDatum* for use in the final gridding process.

6. *MB-System* is an open source software package for the processing and display of bathymetry and backscatter imagery data derived from multibeam, interferometry, and sidescan sonars. The source code for *MB-System* is freely available (for free) by anonymous ftp (including "point and click" access through these web pages). A complete description is provided in web pages accessed through the web site. *MB-System* was originally developed at the Lamont-Doherty Earth Observatory of Columbia University (L-DEO) and is now a collaborative effort between the Monterey Bay Aquarium Research Institute (MBARI) and L-DEO. The National Science Foundation has provided the primary support for *MB-System* development since 1993. The Packard Foundation has provided significant support through MBARI since 1998. Additional support has derived from SeaBeam Instruments (1994-1997), NOAA (2002-2004), and others. URL: http://www.ldeo.columbia.edu/res/pi/MB-System/ [Extracted from *MB-System* web site.]

Table 6. NGDC multibeam swath sonar surveys used in compiling the Santa Monica NAVD 88 DEM.

Survey ID	***Date***	***Institution***	***Ship***
A-3-98-SC	1998	USGS	Ocean Alert
AT15L11	2006	Woods Hole Oceanographic Institution (WHOI)	Atlantis
AT3L14	1998	WHOI	Atlantis
AT3L20	1998	WHOI	Atlantis
C-1-96-SC	1996	USGS	Coastal Surveyor
C-1-99-SC	1998	USGS	Coastal Surveyor
CALF01RR	1996	Scripps Institution of Oceanography (SIO)	Roger Revelle
Channel	1998	Monterey Bay Aquarium Research Institute	Ocean Alert
CNTL04RR	2003	SIO	Roger Revelle
DRFT01RR	2001	SIO	Roger Revelle
E-1-04-SC	2004	Columbia University, Lamont-Doherty Earth Observatory (CU/LDEO)	Maurice Ewing
EW0209	2002	CU/LDEO	Maurice Ewing
EW0407	2004	CU/LDEO	Maurice Ewing
EW9415	1994	CU/LDEO	Maurice Ewing
EW9504	1995	CU/LDEO	Maurice Ewing
EW9904	1999	CU/LDEO	Maurice Ewing
GLOR00MV	1992	SIO	Melville
HLY05TI	2005	CU/LDEO	USCGC Healy
KIWI01RR	1997	SIO	Roger Revelle
LWAD99MV	1999	SIO	Melville
NBP0206A	2002	CU/LDEO	Nathaniel B. Palmer
NPAL98MV	1998	SIO	Melville
NV9704MV	1997	SIO	Melville
OXMZ01MV	1999	SIO	Melville
REVT01RR	1996	SIO	Roger Revelle
WEST15MV	1995	SIO	Melville

3) U.S. Army Corps of Engineers hydrographic surveys

Two channel line survey datasets in xyz format were downloaded from the USACE Los Angeles District ftp site (ftp://ftp.usace.army.mil/pub/spl/; Table 7; Figs. 9 and 11). These surveys, horizontally referenced to NAD 83 California State Plane V and vertically referenced to MLLW, were transformed to NAD 83 geographic using *FME* and transformed to NAVD 88 using *VDatum*.

Table 7. USACE hydrographic surveys used in compiling the Santa Monica DEMs.

Survey name	*Year*	*Original Vertical Datum*	*Original Horizontal Datum*	*Resolution*
Long Beach Harbor	2007	MLLW (meters)	NAD 83 California State Plane V	~ 3 meters
Port of Los Angeles Main Channel	2007	MLLW (feet)	NAD 83 California State Plane V	~ 3 meters

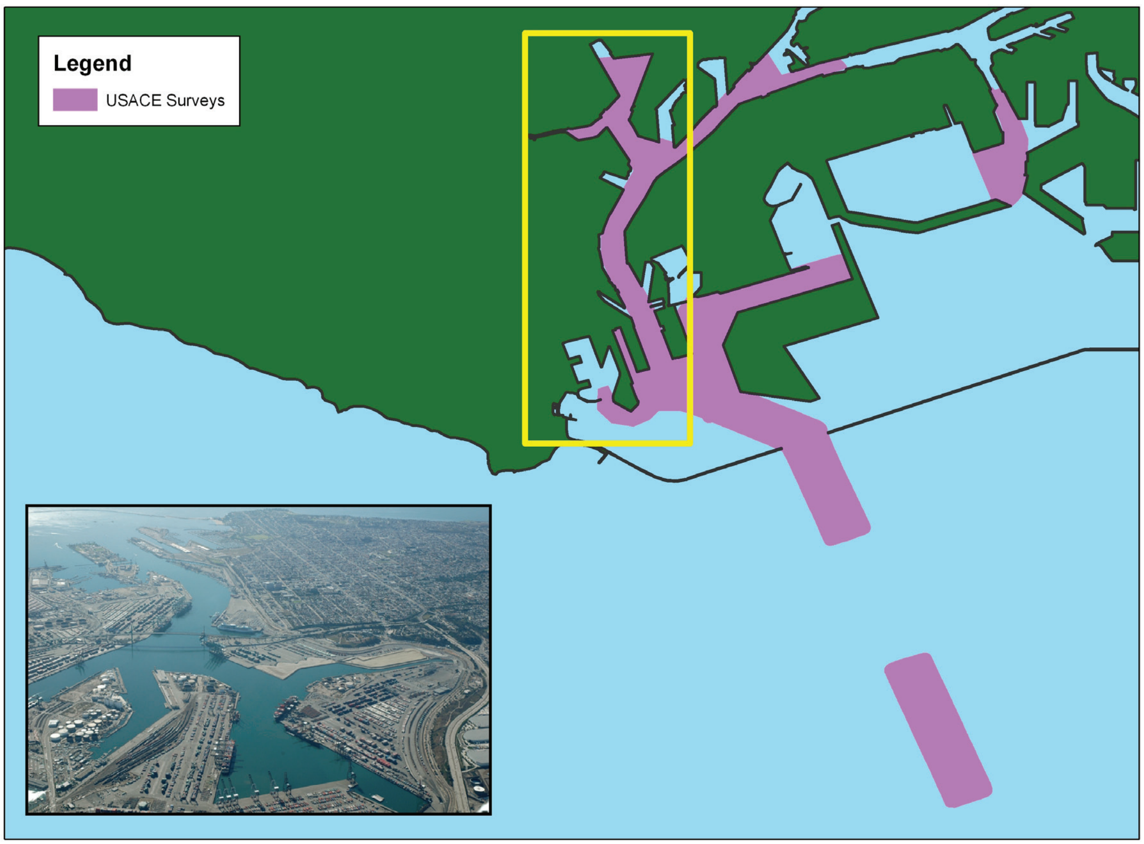

Figure 11. Spatial coverage of USACE hydrographic survey data in the vicinity of Los Angeles and Long Beach Harbors. Inset image of the western portion of Los Angeles Harbor. Yellow box shows approximate location of the inset image. Source: http://www.cnsm.csulb.edu/departments/geology/people/bperry/AerialPhotosSoCal/AerialPhotographyIndexMapPage.htm

4) California State University at Monterey Bay multibeam swath sonar surveys

As part of the California Statewide Mapping Program, CSUMB conducted multibeam sonar surveys for the Santa Monica region from 2001 to 2008 (see Fig. 9). Data used in this study were acquired, processed, archived, and distributed by CSUMB. Four gridded bathymetric datasets for Santa Monica Bay, Santa Catalina Island (Fig. 12), and Santa Barbara Island and Channel were downloaded from CSUMB (Table 8). The grids were horizontally referenced to either NAD 83 UTM Zone 11 North or WGS 84 UTM Zone 11 North and vertically referenced to NAVD 88 or MLLW. Horizontal transformations to NAD 83 were performed using *FME*; vertical transformations were performed using *VDatum*.

Table 8. CSUMB multibeam swath sonar surveys used in compiling the Santa Monica DEMs.

Survey name	*Year*	*Original Vertical Datum*	*Original Horizontal Datum*	*Type*
Santa Catalina Island	2008	NAVD 88	NAD 83 UTM Zone 11N	5 meter grid
Santa Barbara Island	2006/2007	NAVD 88	NAD 83 UTM Zone 11N	2 meter grid
Santa Barbara Channel	2001/2006	MLLW	WGS 84 UTM Zone 11N	2 meter grid
Santa Monica Bay	2002	MLLW	WGS 84 UTM Zone 11N	2 meter grid

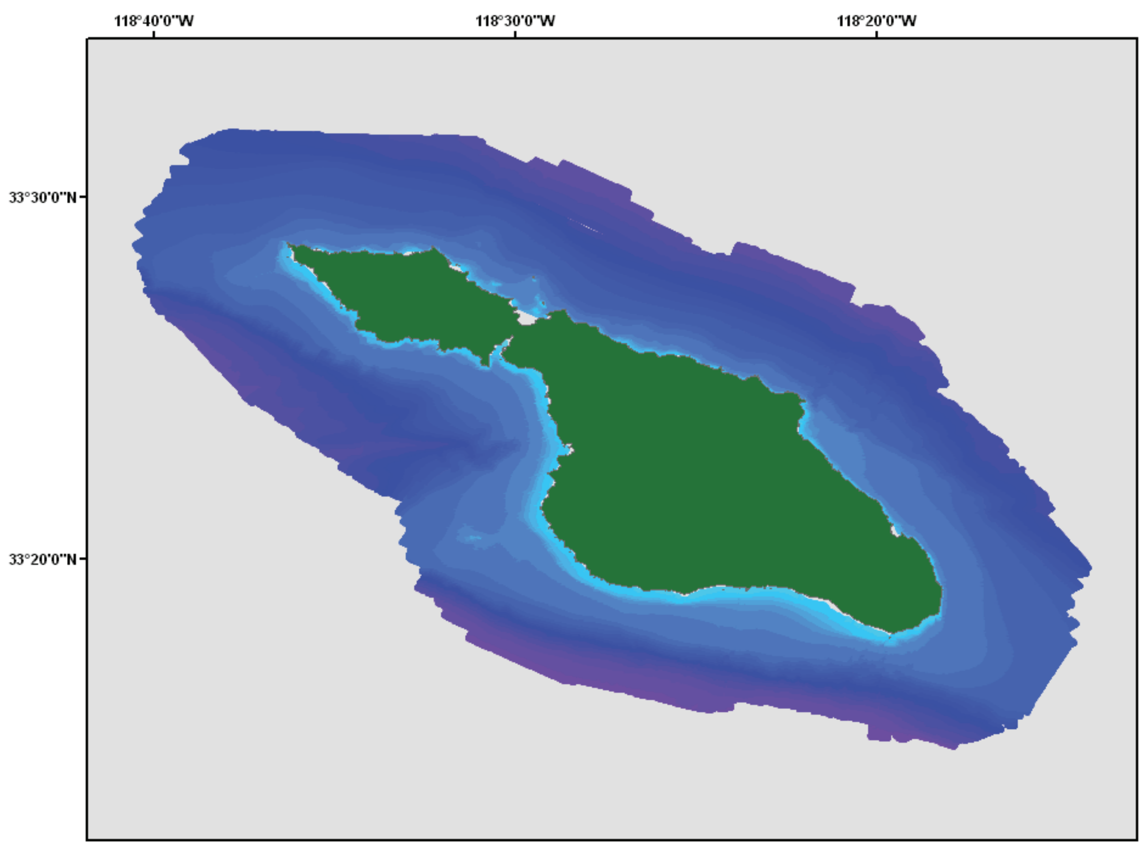

Figure 12. CSUMB multibeam coverage amd shaded depths for the 2008 Santa Catalina Island survey.

5) Electronic navigation chart soundings

Soundings from ENC #18720, 18725, 18740, 18746, 18749, and 18756 were used to supplement other bathymetric data, particularly in the deep water where limited data existed (see Fig. 9; Table 3). The ENCs were downloaded from NOAA's Office of Coast Survey web site and were horizontally referenced to NAD 83 geographic. ENC soundings were included in the gridding process only in regions where higher resolution and/or newer datasets were unavailable (e.g, Fig. 13). The extracted soundings were transformed from a vertical datum of MLLW to NAVD 88 using *VDatum.*

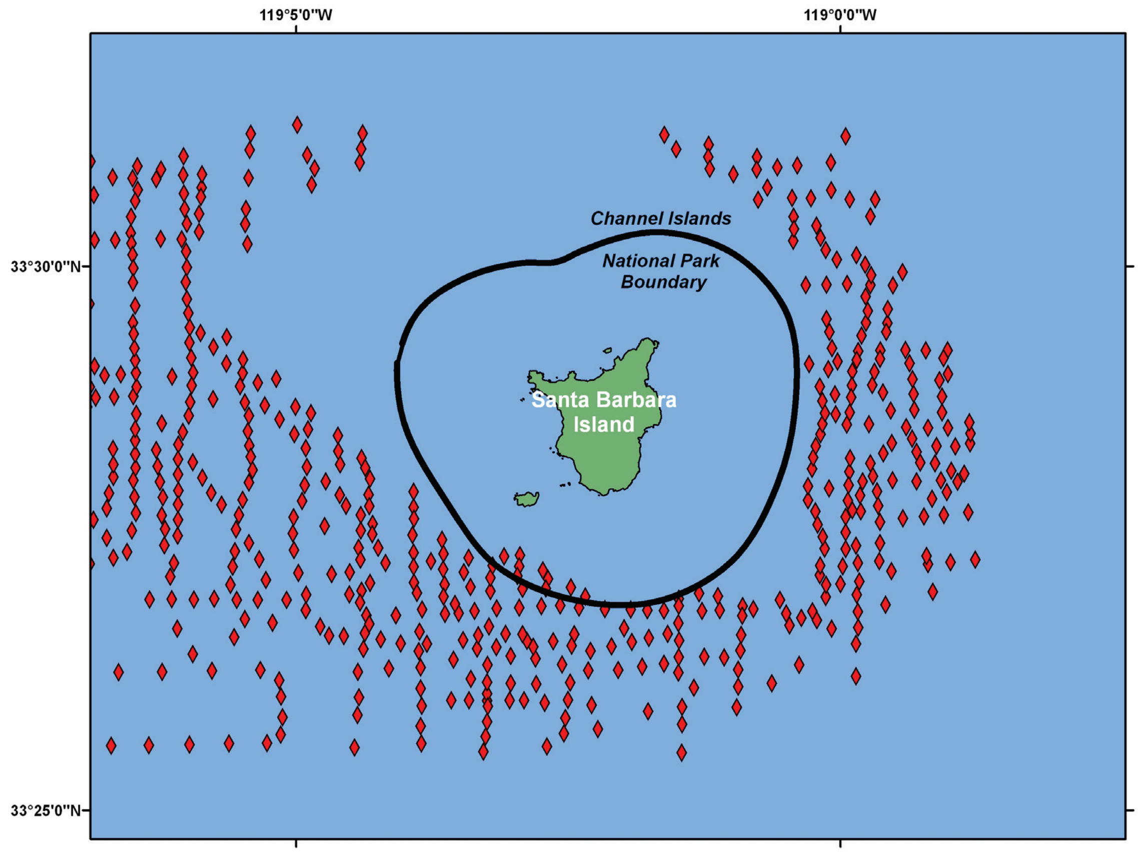

Figure 13. Spatial coverage of extracted soundings from ENC #18756 in the vicinity of Santa Barbara Island. CSUMB multibeam provided coverage within the Channel Islands National Park boundary where ENC extracted soundings were removed prior to the gridding process.

3.1.3 Topography

Six topographic datasets in the Santa Monica region, obtained from CSC, USACE, Ventura County, and USGS, were used to build the Santa Monica NAVD 88 DEM (Table 9; Fig. 14). In addition, NGDC digitized elevation points along several jetties and the wharves in Los Angeles and Long Beach Harbors as they were not resolved completely in the other topographic datasets.

Table 9. Topographic datasets used in compiling the Santa Monica DEMs.

Source	*Year*	*Data Type*	*Spatial Resolution*	*Original Horizontal Datum/Coordinate System*	*Original Vertical Datum*	*URL*
USGS	1999	NED DEM	1/3 arc-second	NAD 83 geographic	NAVD 88	http://ned.usgs.gov/
USGS	2009	NED DEM	1/9 arc-second	NAD 83 geographic	NAVD 88	http://ned.usgs.gov/
CSC	1998	Lidar	2-3 meters	NAD 83 geographic	NAVD 88	http://csc.noaa.gov/digitalcoast/
CSC	2006	Lidar	2-3 meters	NAD 83 geographic	NAVD 88	http://csc.noaa.gov/digitalcoast/
Ventura County	2005	Bare-earth lidar	1 meter	NAD 83 California State Plane V (feet)	NAVD 88	
USACE	2002	Lidar	4 meters	NAD 83 California State Plane V (meters)	NAVD 88	ftp://ftp.usace.army.mil/
NGDC	2009	Digitized elevation points	~ 10 meters	WGS 84 geographic	NAVD 88	

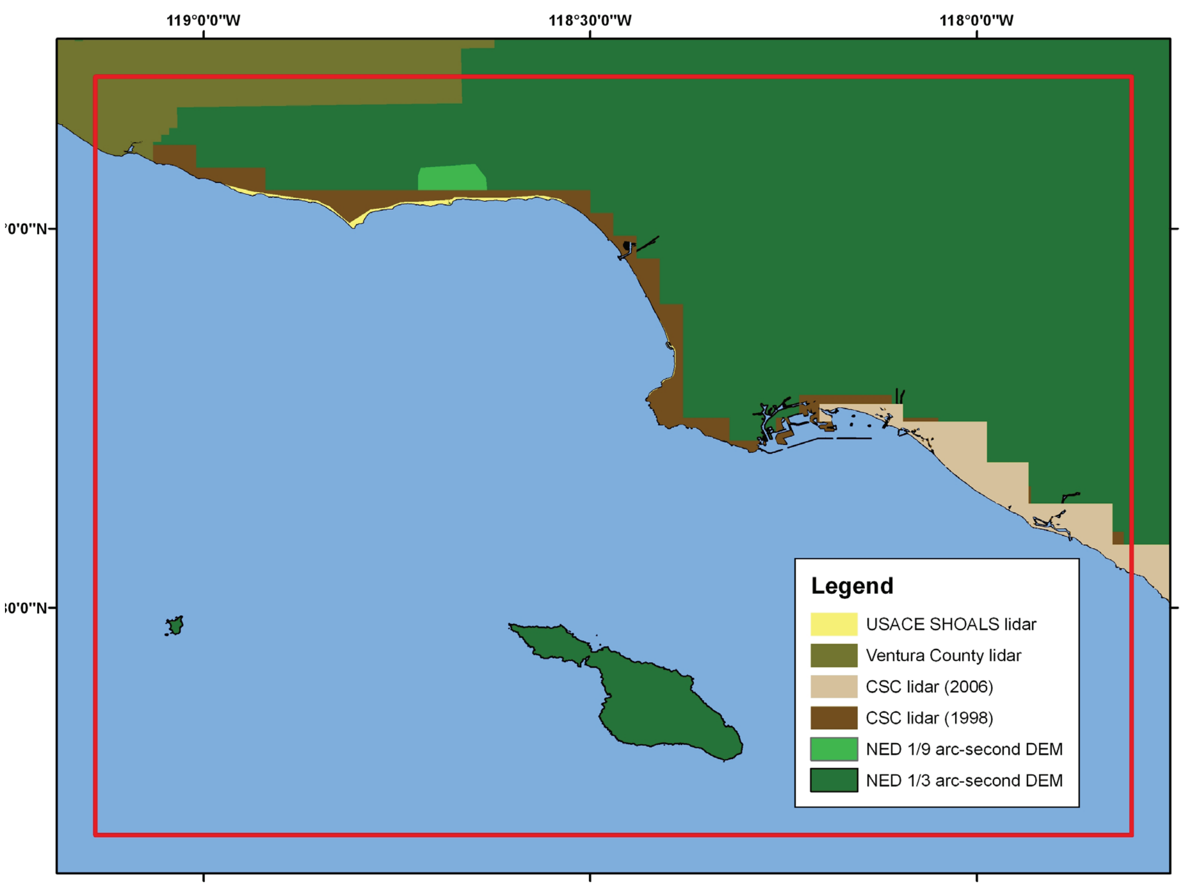

Figure 14. Source and coverage of topographic datasets used in compiling the Santa Monica NAVD 88 DEM.

1) U.S. Geological Survey NED 1/3 DEM

USGS National Elevation Dataset (NED) provides complete 1/3 arc-second coverage of the Santa Monica region[7]. The dataset is available for download as raster DEMs in NAD 83 geographic horizontal datum and NAVD 88 vertical datum (meters). The bare-earth elevations have a vertical accuracy of +/- 7 to 15 meters depending on source data resolution (see the USGS Seamless web site for specific source information: http://seamless.usgs.gov/). The dataset was derived from USGS quadrangle maps and aerial photographs based on topographic surveys.

The USGS NED 1/3 arc-second DEM data were downloaded from the USGS web site. *FME* was used to convert raster data to xyz format. The data were edited to remove anomolous elevation values over the water using *FME*. A comparison of contour lines generated from the NED raster data (NAVD 88) to the USGS topographic quadrangles showed that the NED DEMs in the Santa Monica region are in a mixed vertical datum of NAVD 88 inland and of MHW at the coast (see *Lim et al., 2009* for further details). To partially correct for this, elevations in this dataset that were below 1.9 meters were converted to 1.9 meters, roughly 0.5 meters larger than the difference between NAVD 88 and MHW in the Santa Monica region. This prevented some coastal areas from inappropriately "flooding" with each tidal cycle in the MHW DEM.

2) U.S. Geological Survey NED 1/9 DEM

USGS National Elevation Dataset (NED) provides 1/9 arc-second coverage of the region of the Canyon Fire near Point Dume and Malibu, which incorporated a 2007 lidar survey from the USGS (Fig. 15). The dataset is available for download as a raster DEM in NAD 83 geographic horizontal datum and NAVD 88 vertical datum (meters). The bare-earth elevations in the lidar source dataset have sub-centimeter vertical accuracy with horizontal accuracy of approximately 1 meter. The USGS NED 1/9 arc-second DEM data were downloaded from the USGS web site. The raster data were edited to remove anomolous elevation values over the water using *FME* and then converted to xyz format for use in the gridding process.

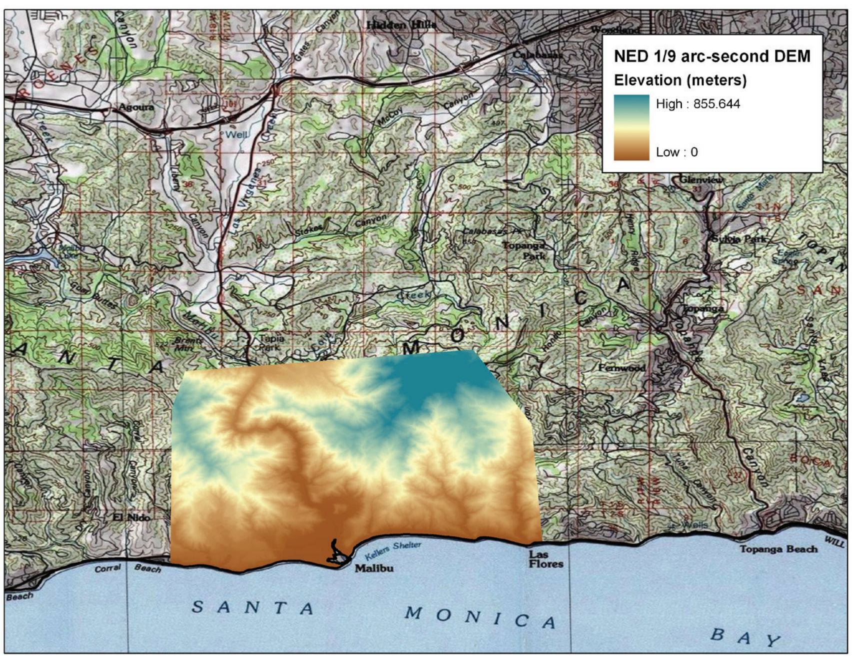

Figure 15. Coverage of NED 1/9 arc-second DEM. Background image is from ESRI U.S. Topo Map (http://resources.arcgis.com/).

7. The USGS National Elevation Dataset (NED) has been developed by merging the highest-resolution, best quality elevation data available across the United States into a seamless raster format. NED is the result of the maturation of the USGS effort to provide 1:24,000-scale Digital Elevation Model (DEM) data for the conterminous U.S. and 1:63,360-scale DEM data for Georgia. The dataset provides seamless coverage of the United States, HI, AK, and the island territories. NED has a consistent projection (Geographic), resolution (1 arc second), and elevation units (meters). The horizontal datum is NAD 83, except for AK, which is NAD 27. The vertical datum is NAVD 88, except for AK, which is NGVD29. NED is a living dataset that is updated bimonthly to incorporate the "best available" DEM data. As more 1/3 arc second (10 m) data covers the U.S., then this will also be a seamless dataset. [Extracted from USGS NED web site]

3) Coastal Services Center 1998 non-bare-earth topographic lidar

A Spring 1998 Post El-Nino topographic non-bare-earth lidar survey was downloaded from the CSC web site. The data were collected during the Airborne LiDAR Assessment of Coastal Erosion (ALACE) Project. The ALACE project was a partnership between NOAA, National Aeronautics and Space Administration (NASA), and USGS. It has been collecting baseline coastal topographic data for the conterminous U.S. since 1996. The ALACE collections are typically targeted at a narrow strip of sandy beach and are usually a kilometer or less in width. In general, this data has not been checked with ground control, but has undergone internal consistency checks. All flights are timed to occur within a few hours of low tide, when the beach is most exposed. The survey has a vertical accuracy of approximately 15 centimeters for bare ground, however the survey was not processed to bare earth and exhibits much larger errors, particularly in regions of development along the coast. The horizontal accuracy is 80 centimeters. The data were downloaded in xyz format in NAD 83 geographic horizontal datum and NAVD 88 vertical datum. The xyz files were converted to shapefiles using *FME*.

This survey covers the coastline from the eastern boundary of Ventura County to east of Long Beach, California (see Fig. 14). Since the data were not processed to bare earth (e.g., Fig. 16), the survey was edited to include only elevations of 5 meters or less and clipped to the coastline to eliminate water returns, piers, and large buildings using *FME*. NGDC manually removed remaining buildings from the dataset using *QT Modeler*.

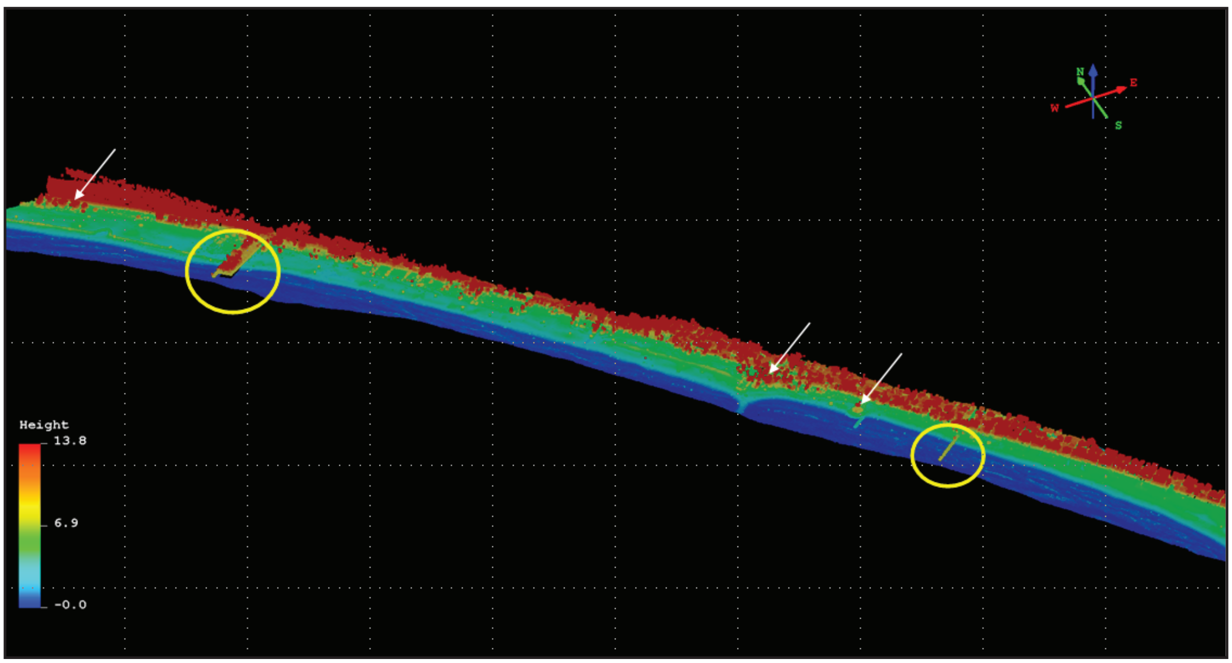

Figure 16. Perspective view of Spring 1998 CSC lidar data. Arrows point to anomalous returns in lidar from vegetation. Yellow circles indicate piers. Piers and vegetation were removed using FME and QT Modeler. Vertical exaggeration 5 times.

4) Coastal Services Center 2006 non-bare-earth topographic lidar

A 2006 topographic non-bare-earth lidar survey was downloaded from the CSC web site. The data were collected by Scripps Institution of Oceanography for southern California to monitor rates of shoreline change. The survey has a vertical accuracy of approximately 10 centimeters for bare ground, however the survey was not processed to bare earth and exhibits much larger errors, particularly in regions of development along the coast. The horizontal accuracy is 1 meter. The data were downloaded in xyz format in NAD 83 geographic horizontal datum and NAVD 88 vertical datum. The xyz files were converted to shapefiles using *FME*.

The survey covered the region from Long Beach, California to the U.S.-Mexico border (see Fig. 14). Since the data were not processed to bare earth (e.g., Fig. 17), the survey was edited to include only elevations of 5 meters or less and clipped to the coastline to eliminate water returns, piers, and large buildings using *FME*. NGDC manually removed remaining building returns from the dataset using *QT Modeler*.

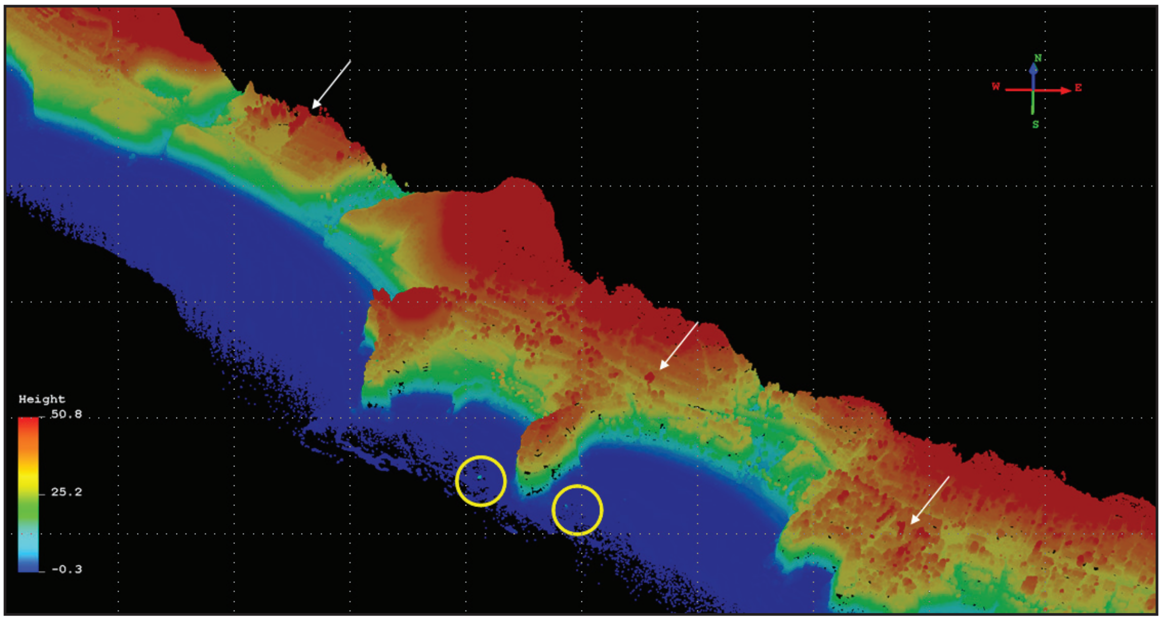

Figure 17. Perspective view of 2006 CSC lidar data. Arrows point to anomalous returns in lidar from vegetation. Yellow circles indicate spurious water returns. Errors were removed using FME and QT Modeler. Vertical exagerration 5 times.

5) Ventura County bare-earth lidar

Ventura County provided NGDC with bare-earth lidar point data flown in February of 2005. The point data were transformed to NAD 83 geographic with *FME* and clipped to the combined coastline prior to use in the final gridding process.

6) USACE non-bare-earth lidar

A 2002 topographic non-bare-earth lidar survey was downloaded from the USACE web site. The data were collected as part of the Scanning Hydrographic Operational Airborne Lidar Survey (SHOALS) system, which consists of an airborne laser transmitter/receiver and a ground-based processing system. The purpose of this survey was to determine the existing conditions of the beach and shoreline. The SHOALS data were received in NAD 83 California State Plane V horizontal datum and NAVD 88 (meters) vertical datum. The vertical accuracy is approximately 15 centimeters and the horizontal accuracy is ~ 3 meters.

Since the data were not processed to bare earth, the survey was edited to include only elevations of 5 meters or less and clipped to the coastline to eliminate water returns, piers, and large buildings using *FME*. Figure 18 shows the region surrounding Redondo Beach where breakwaters were well represented in the lidar data, but docks and piers near-shore had to be manually removed. NGDC also manually removed remaining building returns from the dataset using *QT Modeler*.

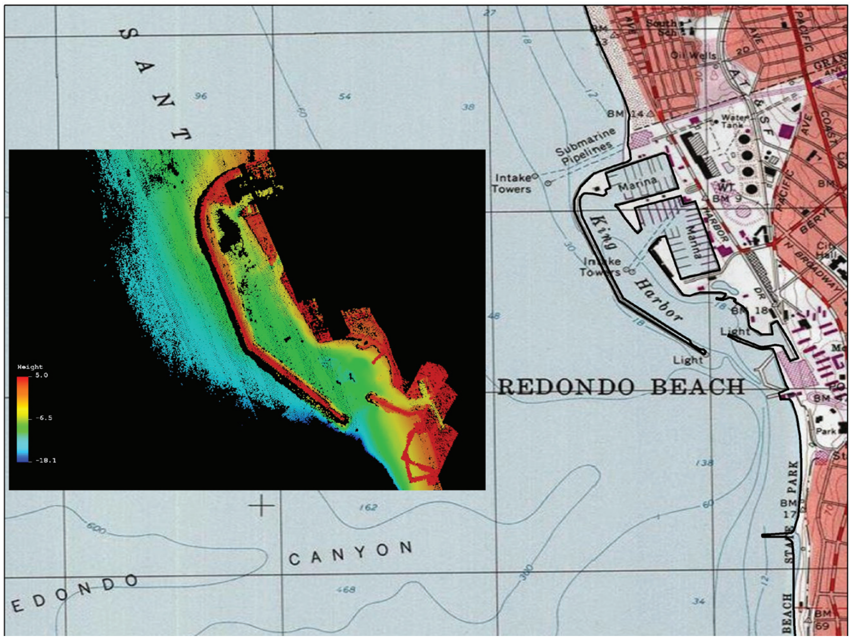

Figure 18. Image of the USACE lidar survey of the breakwater at Redondo Beach. ESRI U.S. Topo Map is in the background.

7) NGDC digitized elevation points

In Los Angeles and Long Beach Harbors, CSC and USACE lidar did not provide complete coverage of the breakwaters and wharves. Using the available lidar elevations from CSC and USACE as references, NGDC digitized a point shapefile to represent the elevations at 10 meters point spacing (Fig. 19). Generally, the elevations of the wharves ranged from 3 to 3.5 meters based on harbor survey drawings provided by the Port of Long Beach. Breakwaters were digitized at 1 to 2 meters. Several regions also required supplemental elevation point data to maintain positive values on land in the MHW DEM.

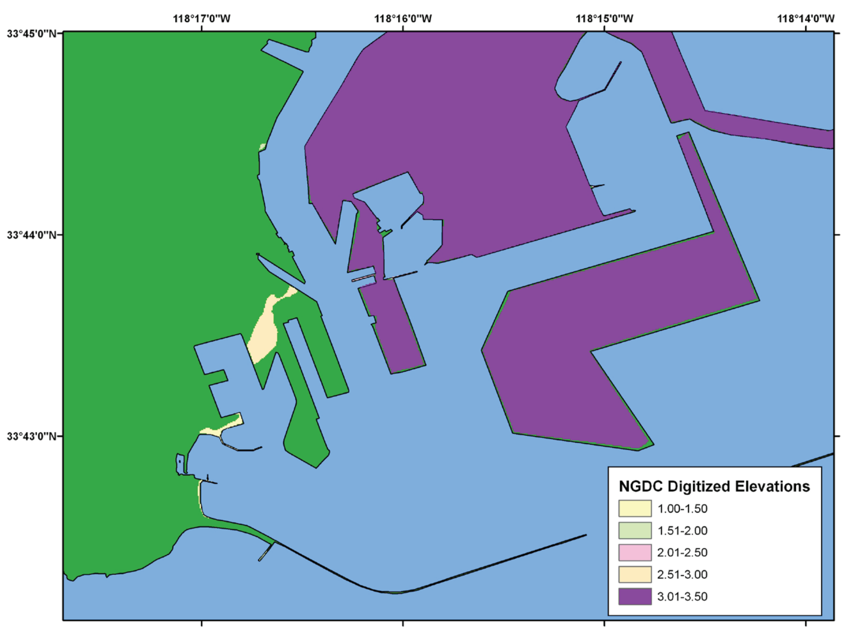

Figure 19. Digitized elevation points in Los Angeles Harbor. Water is indicated in blue and undigitized land surfaces in dark green.

3.2 Establishing Common Datums

3.2.1 Vertical datum transformations

Datasets used in the compilation and evaluation of the Santa Monica NAVD 88 DEM were originally referenced to a number of vertical datums including MLLW, MSL, and NAVD 88. All datasets were transformed to NAVD 88 using the *VDatum* transformation tool (http://vdatum.noaa.gov/). The tidal relationships at the Santa Monica tide station (http://tidesandcurrents.noaa.gov/) are provided in Table 10.

1) **Bathymetric data**

   The NOS hydrographic surveys, multibeam swath sonar surveys, ENC soundings, and USACE surveys were transformed from MLLW and MSL to NAVD 88 using *VDatum*.

2) **Topographic data**

   The topographic datasets were originally referenced to NAVD 88 requiring no vertical transformations.

Table 10. Relationship between NAVD 88 and other vertical datums at the Santa Monica tide station (# 9410840).

Vertical datum	*Value*	*Difference to NAVD 88*
MHHW	2.40	1.60
MHW	2.17	1.37
MSL	1.59	0.79
MLW	1.03	0.23
NAVD 88	0.80	0.00
MLLW	0.74	-0.06

3.2.2 Horizontal datum transformations

Datasets used to compile the Santa Monica NAVD 88 DEM were originally referenced to WGS 84 geographic, NAD 83 geographic, NAD 83 UTM Zone 11 North, WGS 84 UTM Zone 11 North, and NAD 83 California State Plane V (feet and meters) horizontal datums. The relationships and transformational equations between the geographic horizontal datums are well established. Transformations to NAD 83 geographic were accomplished using *FME* software.

3.3 Digital Elevation Model Development

3.3.1 Verifying consistency between datasets

After horizontal and vertical transformations were applied, the resulting ESRI shapefiles were checked in *ArcMap* and *QT Modeler* for inter-dataset consistency. Problems and errors were identified and resolved before proceeding with subsequent gridding steps. The evaluated and edited ESRI shapefiles were then converted to xyz files in preparation for gridding. Problems included:

- Inconsistent, overlapping high-resolution topographic datasets. Datasets were weighted based on quality and year during the gridding process.
- Data values over the ocean in the NED DEMs, CSC lidar, USACE lidar, and Ventura County lidar topographic datasets. These datasets required automated clipping to the combined coastline or were edited manually.
- Discrepancies in NED DEM vertical datum. NGDC assigned an NAVD 88 elevation value of 1.9 meters to cells below 1.9 meters.
- Digital, measured bathymetric values from NOS surveys date back over 70 years. More recent data, such as the multibeam surveys, differed from older NOS data by as much as 50 meters vertically. The older NOS survey data were excised where more recent bathymetric data exists.
- Returns from vegetation and buildings in lidar datasets. Anomalous returns were removed by eliminating elevations greater than 5 meters and then manually edited to remove remaining anomalies where possible.
- Some wharves in Los Angeles and Long Beach Harbors are not well-represented in available elevation data. Limited lidar data in the region and harbor survey drawings from Port of Long Beach were used to estimate a constant elevation surface for the wharves.

3.3.2 Smoothing of bathymetric data

The older NOS hydrographic survey data are generally sparse at the resolution of the Santa Monica DEMs in both deep water and in some areas close to shore. In order to reduce the effect of artifacts in the form of lines or “pimples” in the DEM due to these low resolution datasets, and to provide effective interpolation into the coastal zone, a 1 arc-second-cell size ‘pre-surface’ bathymetric grid in NAVD 88 vertical datum was generated using *GMT*[8], an NSF-funded share-ware software application designed to manipulate data for mapping purposes (http://gmt.soest.hawaii.edu/).

The NOS hydrographic point data, in xyz format, were clipped to remove overlap with the newer NOS surveys, NGDC multibeam data, and CSUMB multibeam data. The data were then combined with USACE data, ENC soundings, and points extracted from the adjusted MHW coastline—to provide a buffer along the entire coastline. The coastline elevation values were set to 0.50 meters to ensure a bathymetric surface approaching zero relative to MHW in areas where bathymetric data are sparse or non-existent.

The point data were then median-averaged using the *GMT* tool ‘blockmedian’ to create a 1 arc-second grid 0.05 degrees (~5%) larger than the Santa Monica DEM gridding region. The *GMT* tool ‘surface’ was then used to apply a tight spline tension to interpolate elevations for cells without data values. The netcdf grid created by ‘surface’ was converted into an ESRI Arc ASCII grid file, and clipped to the combined coastline (to eliminate data interpolation into land areas). The resulting surface was compared with original soundings to ensure grid accuracy. Figures 20-22 shows histograms of the NOS, NGDC multibeam, and USACE surveys compared to the 1 arc-second pre-surfaced bathymetric grid. Differences cluster around zero with a range of -20 to +20 meters when compared to the bathymetric surface. Points with the largest differences are located along steep gradients of elevation (e.g., submarine canyons) where the high-resolution surveys may include over 100 points that are averaged to a single cell elevation value. Overlapping high-resolution surveys from different years also lead to some of the larger errors.

Some inconsistencies were identified while merging the bathymetric datasets due to the range in ages and resolutions of the NOS hydrographic surveys. In areas where more recent data were available, the older surveys were either edited or not used. The gridded bathymetric surface was then converted to an xyz file for use in building the NAVD 88 DEM.

9. GMT is an open source collection of ~60 tools for manipulating geographic and Cartesian data sets (including filtering, trend fitting, gridding, projecting, etc.) and producing Encapsulated PostScript File (EPS) illustrations ranging from simple x-y plots via contour maps to artificially illuminated surfaces and 3-D perspective views. GMT supports ~30 map projections and transformations and comes with support data such as GSHHS coastlines, rivers, and political boundaries. GMT is developed and maintained by Paul Wessel and Walter H. F. Smith with help from a global set of volunteers, and is supported by the National Science Foundation. It is released under the GNU General Public License. URL: http://gmt.soest.hawaii.edu/ [Extracted from GMT web site.]

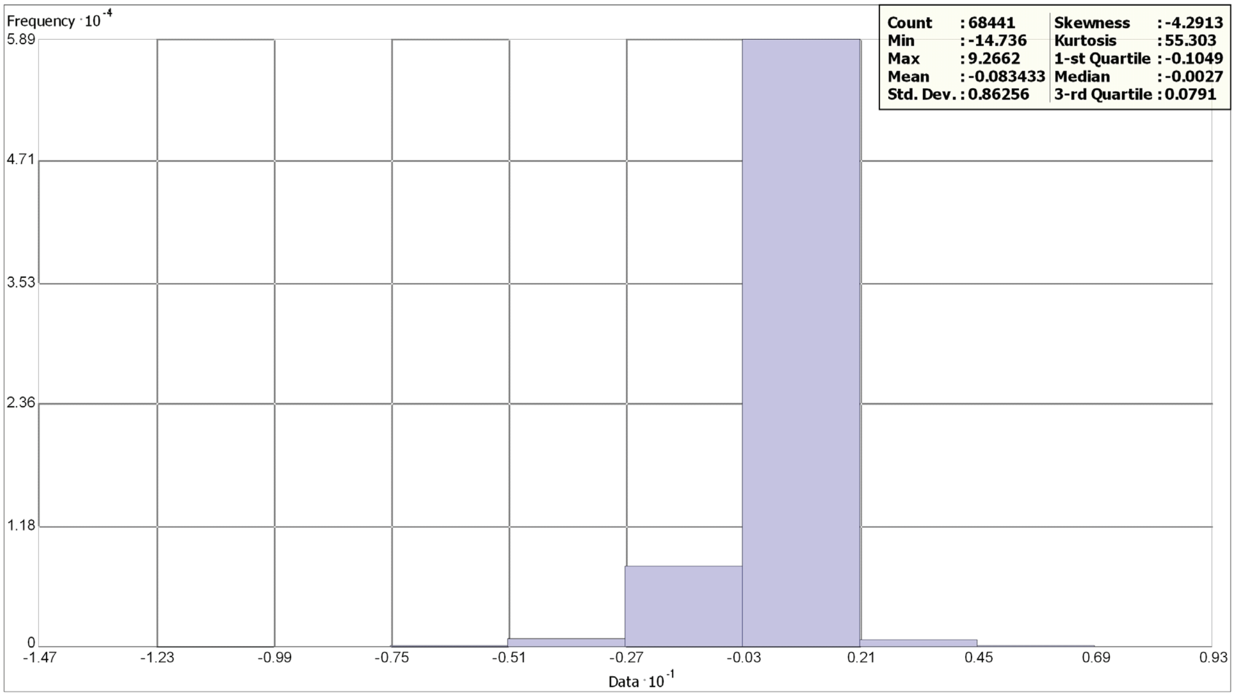

Figure 20. Histogram of the differences between all NOS hydrographic surveys and the 1 arc-second pre-surfaced bathymetric grid.

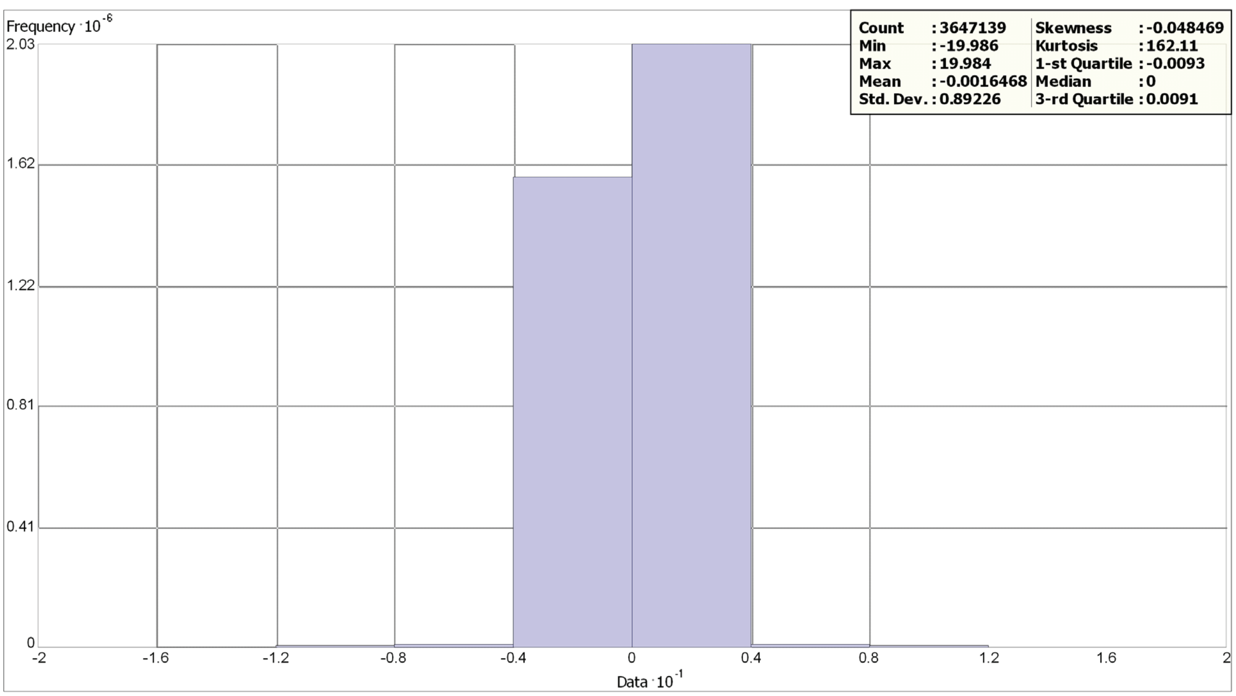

Figure 21. Histogram of the differences between all NGDC multibeam swath sonar surveys and the 1 arc-second pre-surfaced bathymetric grid.

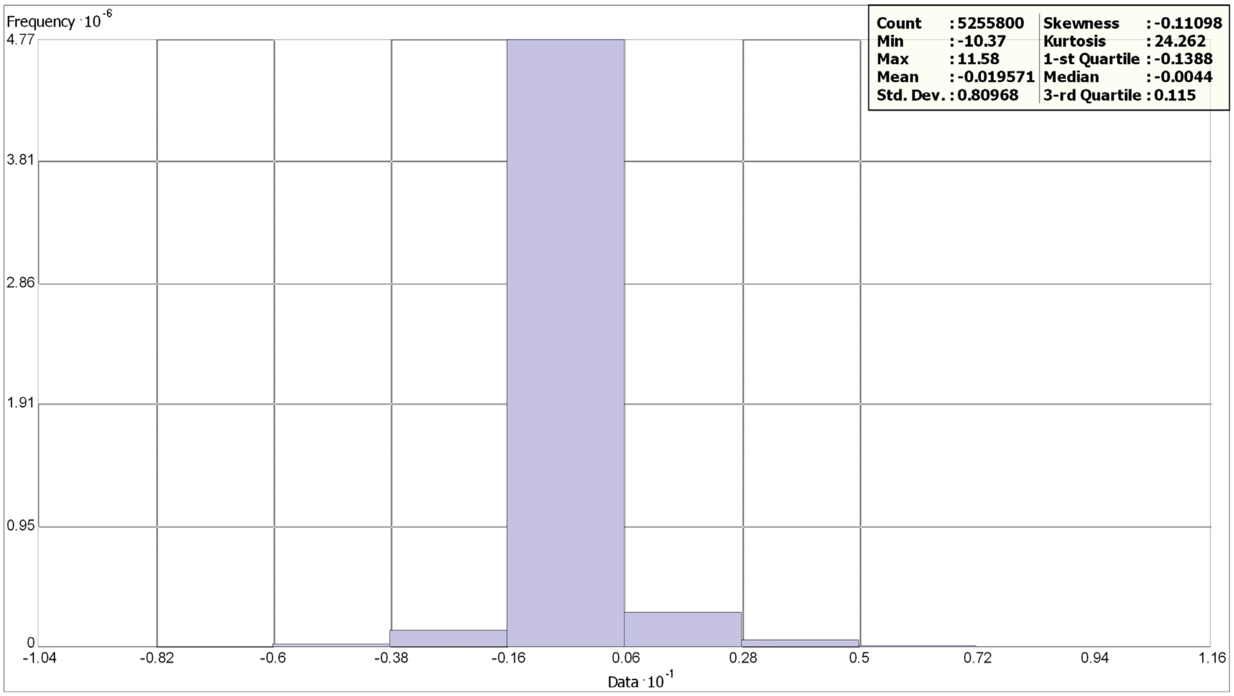

Figure 22. Histogram of the differences between all USACE hydrographic surveys and the 1 arc-second pre-surfaced bathymetric grid

3.3.3 Building the NAVD 88 DEM

MB-System was used to create the 1/3 arc-second Santa Monica NAVD 88 DEM. The *MB-System* tool 'mbgrid' was used to apply a tight spline tension to the xyz data, and interpolate values for cells without data. The data hierarchy used in the 'mbgrid' gridding algorithm, as relative gridding weights, is listed in Table 11. Greatest weight was given to the high resolution topographic lidar, the high resolution multibeam surveys, NOS BAG data, USACE hydrographic surveys, and the NGDC digitized features. Least weight was given to the pre-surfaced bathymetric grid, NGDC trackline, and ENC soundings.

Table 11. Data hierarchy used to assign gridding weight in *MB-System*

Dataset	*Relative Gridding Weight*
CSUMB multibeam	100
NGDC multibeam	100
USGS multibeam	100
NOS BAGs	100
USACE hydrographic surveys	100
CSC lidar	100
Ventura County lidar	100
USACE lidar	100
NGDC digitized features	100
USGS NED DEM	10
NOS hydrographic surveys	10
ENC soundings	1
NGDC trackline	0.1
Pre-surfaced bathymetric grid	0.1

3.3.4 *Building the MHW DEM*

The MHW DEM was created by adding an NAVD 88-to-MHW conversion grid to the NAVD 88 DEM.

1) Developing the conversion grid

Using extents slightly larger (~ 5 percent) than the DEM, an initial xyz file was created that contained the coordinates of the four bounding vertices and midpoint of the larger extents. The elevation value at each of the points was set to zero. The *GMT* tool 'surface' applied a tension spline to interpolate cell values making a zero-value 3 arc-second grid. This zero-value grid was then converted to an intermediate xyz file using the *GMT* tool 'grd2xyz'.

Conversion values from NAVD 88 to MHW at each xyz point were generated using *VDatum*. Null values were removed and a converted xyz file was created by clipping the data to the combined coastline using *FME*. The converted xyz file was then interpolated with the *GMT* tool 'surface' to create the 1/3 arc-second 'NAVD 88 to MHW' conversion grid with the extents of the NAVD 88 DEM (Fig. 23).

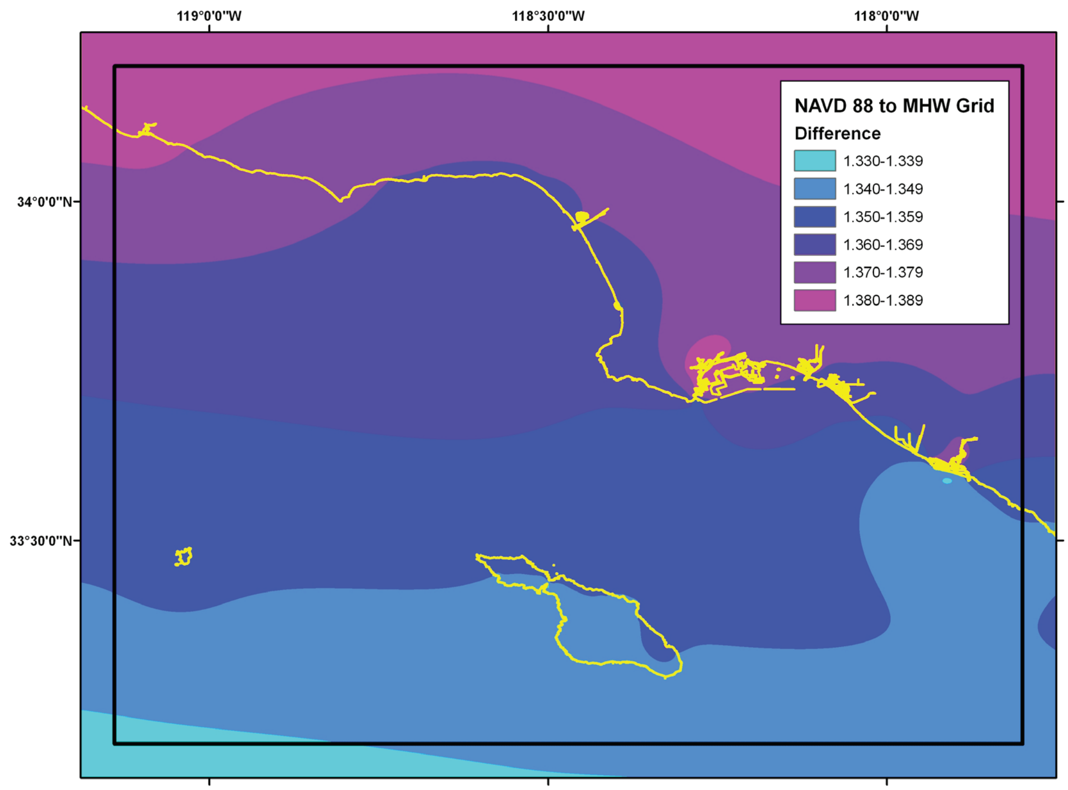

Figure 23. The NAVD 88 to MHW conversion grid used to generate the MHW DEM. Coastline in yellow. Black box denotes DEM boundary.

2) **Assessing the accuracy of the conversion grid**

The NAVD 88-to-MHW conversion grid was assessed using the NOS survey data. For testing of this methodology, the NOS hydrographic survey data were transformed from MLLW to NAVD 88 using *VDatum*. Shapefiles of the resultant xyz files were created and null values removed using *FME*. The shapefiles were then merged to create a single shapefile of all NOS surveys with a vertical datum of NAVD 88. A second shapefile of NOS data were created with a vertical datum of MHW using the same method. Elevation differences between the MHW and NAVD 88 shapefiles were computed after performing a spatial join in *ArcGIS*.

To verify the conversion grid methodology, the difference shapefile created using *ArcGIS* was converted to xyz format using *FME*. The CrossCheck module in *Fledermaus* was used to evaluate the performance of the 1/3 arc-second conversion grid by comparing the 'NAVD 88-to-MHW' grid to the difference xyz file. The *Fledermaus* results indicated agreement to approximately +/- 0.008 meters with a mean difference of 0.002 meters. The *Fledermaus* results were then converted to shapefile format using *FME* to visualize the comparison and to produce a histogram of the variations in *ArcGIS* (Fig. 24).

Errors in the vertical datum conversion method reside for the most part in the NAVD 88-to-MHW conversion grid; most topographic data are already in NAVD 88. Errors in the source datasets require rebuilding only the NAVD 88 DEM.

3) **Creating the MHW DEM**

Once the NAVD 88 DEM was complete and assessed for errors, the conversion grid was added using *ArcCatalog*. The resulting MHW DEM was reviewed and assessed using RNCs, USGS topographic maps, and ESRI *World 2D* imagery. Problems encountered were determined to reside in source datasets, which were corrected before building a new NAVD 88 DEM.

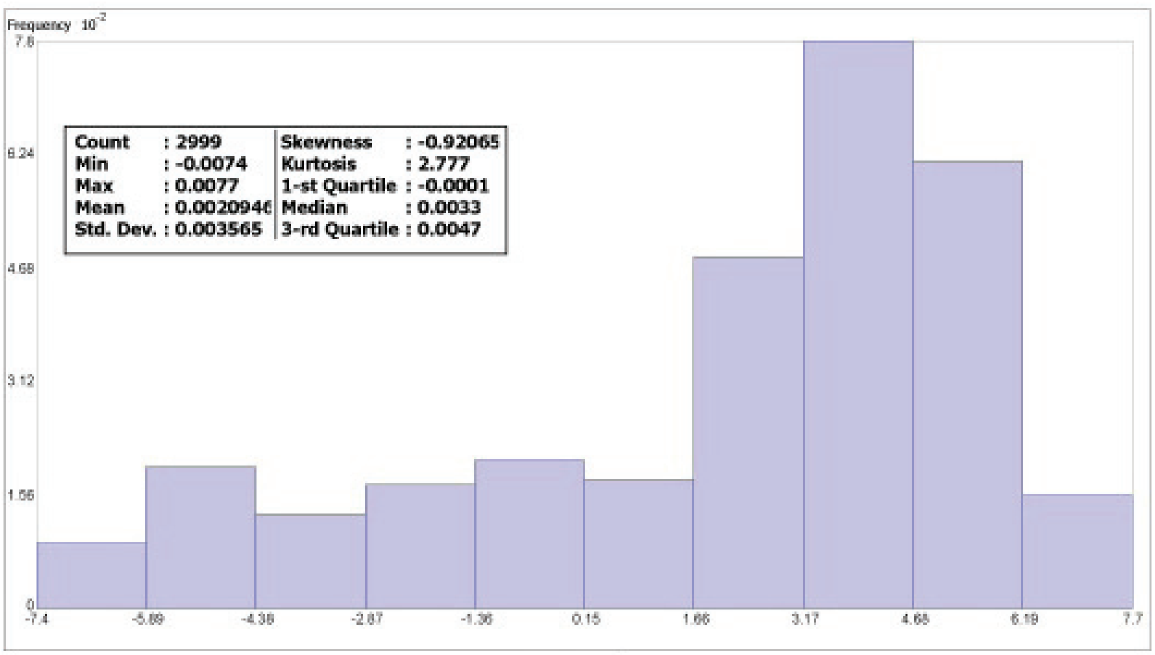

Figure 24. Histogram of the differences between the conversion grid and xyz difference files using NOS hydrographic survey data.

3.4 Quality Assessment of the DEMs

3.4.1 Horizontal accuracy

The horizontal accuracy of topographic and bathymetric features in the Santa Monica DEMs is dependent upon DEM cell size and source datasets. Topographic features have an estimated horizontal accuracy of 10 meters: gridded CSC and USACE lidar data have an accuracy of approximately 1 meter and NED DEM data is accurate to approximately 10 meters. Bathymetric features are resolved only to within a few tens of meters in deep-water areas. Shallow, near-coastal regions, rivers, and harbor surveys have an accuracy approaching that of sub-aerial topographic features. Positional accuracy is limited by the sparseness of deep-water soundings and potentially large positional uncertainty of pre-satellite navigated (e.g., GPS) NOS hydrographic surveys.

3.4.2 Vertical accuracy

Vertical accuracy of elevation values in the Santa Monica DEMs is also dependent upon the source datasets contributing to DEM cell values. Topographic data have an estimated vertical accuracy between 0.1 meters for bare-earth lidar data and 7 meters for NED DEMs. Bathymetric values have an estimated accuracy between 0.1 meters and 5% of water depth. Those values were derived from the wide range of sounding measurements from the early 20th century to recent, GPS-navigated multibeam swath sonar survey. Gridding interpolation to determine bathymetric values between sparse, poorly located NOS soundings degrades the vertical accuracy of elevations in deep water.

3.4.3 Slope map and 3-D perspectives

ESRI *ArcCatalog* was used to generate a slope grid from the Santa Monica NAVD 88 DEM to allow for visual inspection and identification of artificial slopes along boundaries between datasets (Fig. 25). The DEM was transformed to NAD 83 UTM Zone 11 North coordinates (horizontal units in meters) in *ArcCatalog* for derivation of the slope grid; equivalent horizontal and vertical units are required for effective slope analysis. Analysis of preliminary grids using *QT Modeler* and *Fledermaus* revealed suspect data points, which were corrected before recompiling the DEM. Figure 1 shows a color image of the 1/3 arc-second Santa Monica NAVD 88 DEM in its final version. Figure 26 shows a perspective rendering of the final NAVD 88 DEM. Figure 27 shows a data contribution plot of the Santa Monica DEMs.

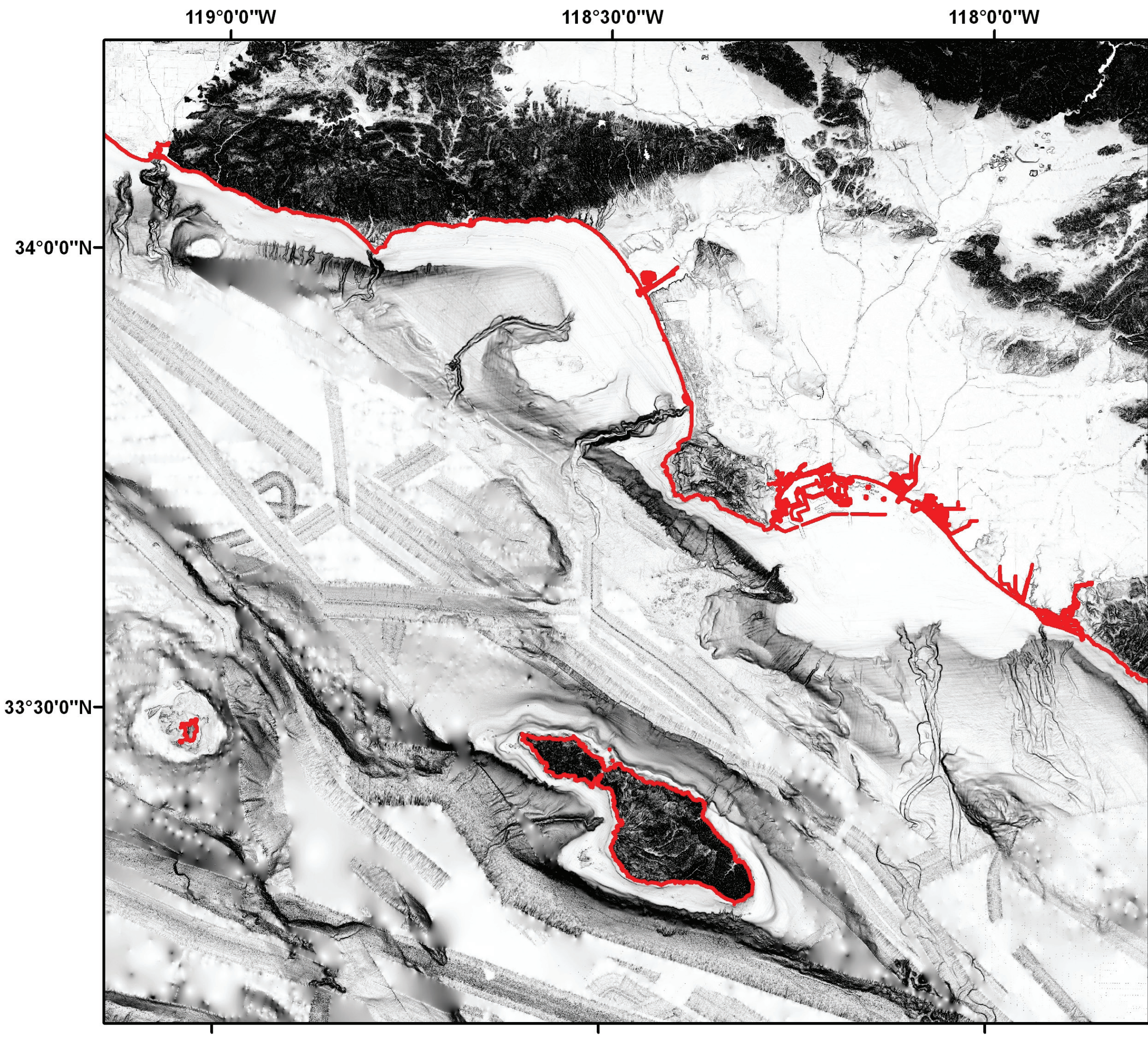

Figure 25. Slope map of the Santa Monica NAVD 88 DEM. Flat-lying slopes are shown in white; dark shading denotes steep slopes; combined coastline indicated in red.

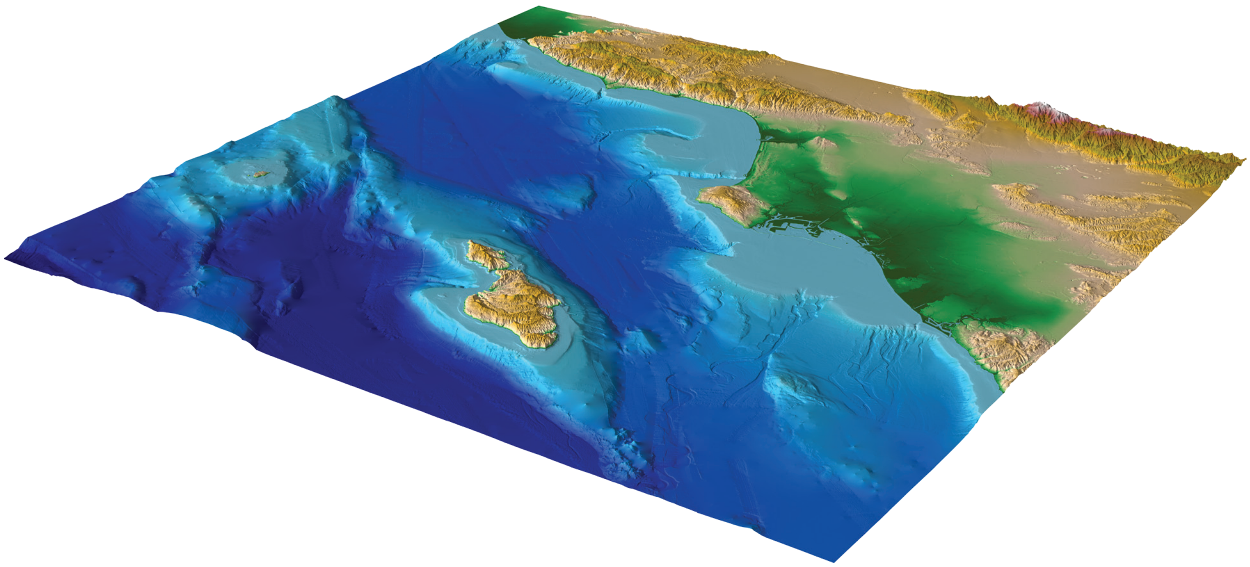

Figure 26. Perspective view from the southeast of the 1/3 arc-second Santa Monica NAVD 88 DEM. Vertical exaggeration–times 2.

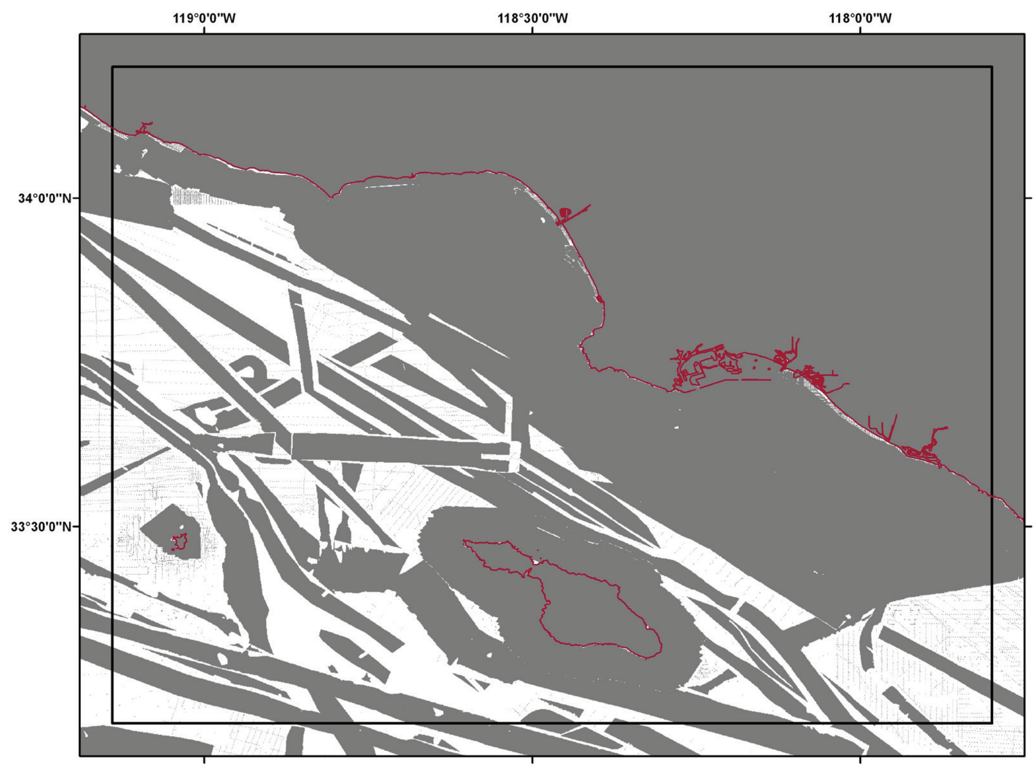

Figure 27. Data contribution plot of the Santa Monica NAVD 88 DEM. Grey depicts DEM cells constrained by source data; white depicts cells with elevation values derived from interpolation. Due to the scale of the image, sparse soundings may not be visible in the graphic. Coastline is shown in red; DEM boundary in black.

3.4.4 Comparison with National Geodetic Survey geodetic monuments

The elevations of 5973 geodetic monuments were extracted from the NOAA NGS web site (http://www.ngs.noaa.gov/) in shapefile format (see Fig. 28 for monument locations). Only 4135 monuments with conditions noted as 'GOOD' or 'MONUMENTED' were included in the analysis. Shapefile attributes give positions in NAD 83 geographic (typically sub-mm accuracy) and elevations in NAVD 88 (in meters). Elevations were compared to the Santa Monica NAVD 88 DEM (Fig. 29). Differences between the DEM and the monument elevations range from -56.117 to 78.98 meters, half of which are within ± 1.5 meters. Large differences in elevations occurred where monuments are located on road cuts, on top of buildings, or have conversion errors evident on the NGS data sheet (e.g., feet instead of meters).

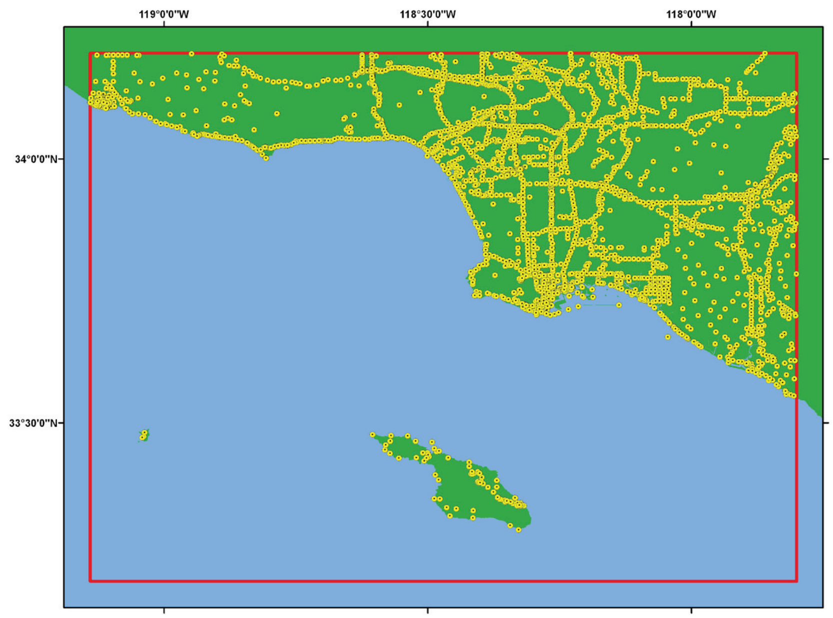

Figure 28. Location of NGS geodetic monuments, shown as yellow circles, in the Santa Monica region.

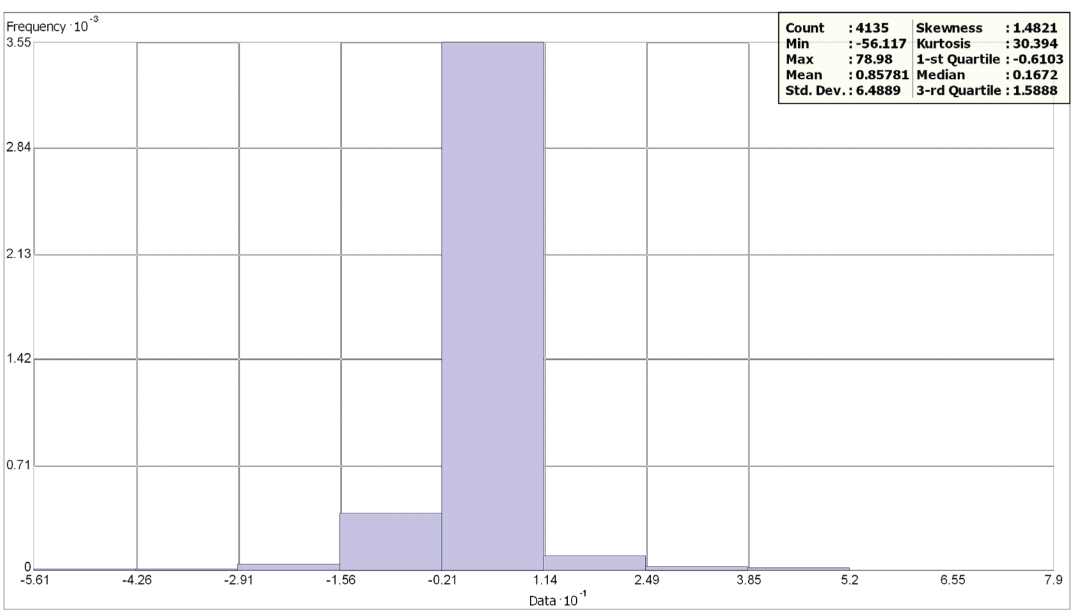

Figure 29. Histogram of the differences between NGS geodetic monument elevations and the Santa Monica NAVD 88 DEM.

3.4.5 NAVD 88 DEM comparison with source data files

To ensure grid accuracy, the Santa Monica NAVD 88 DEM was compared to source data files. Files were chosen on the basis of their contribution to the grid from Table 11. Select bathymetric data and topographic data files were compared to the Santa Monica NAVD 88 DEM using *Fledermaus*, *FME* and *ArcMap*.

A histogram of the differences between 100,000 data points from the NED 1/9 arc-second DEM and the Santa Monica NAVD 88 DEM is shown in Figure 30. Differences cluster around zero. The major differences in elevations in NED data points with the grid (-14.578 meters and +13.059 meters) are located in regions of steep slopes, where several points are averaged to obtain a single elevation value. In addition, the NED DEMs were allowed to overlap with the non-bare-earth lidar datasets along the coast and may introduce some errors due to the inclusion of trees and buildings.

A selection of 100,000 CSC topographic lidar points were compared to the Santa Monica NAVD 88 DEM (Fig. 31). The histogram shows the differences in elevations are clustered around zero and the majority are within ± 2.5 meters. The largest differences are located in regions where the NED was allowed to overlap the lidar to better represent a bare-earth surface.

Comparison of the USACE hydrographic survey data and the Santa Monica NAVD 88 DEM are shown in Figure 32. A subset of 100,000 points was used to compute differences. Elevation differences range from -1.6265 to 1.2768 meters. Large differences occur where the USACE data overlaps other higher resolution datasets, which may occur due to changes in dredged depths or sediment deposition in channels.

A portion of the NGDC multibeam swath sonar surveys were compared with the Santa Monica NAVD 88 DEM. The histogram shows the differences in elevations range from -0.0002 to -0.0003 meters (Fig. 33). The 100,000 selected points from the NGDC multibeam dataset agree with high precision.

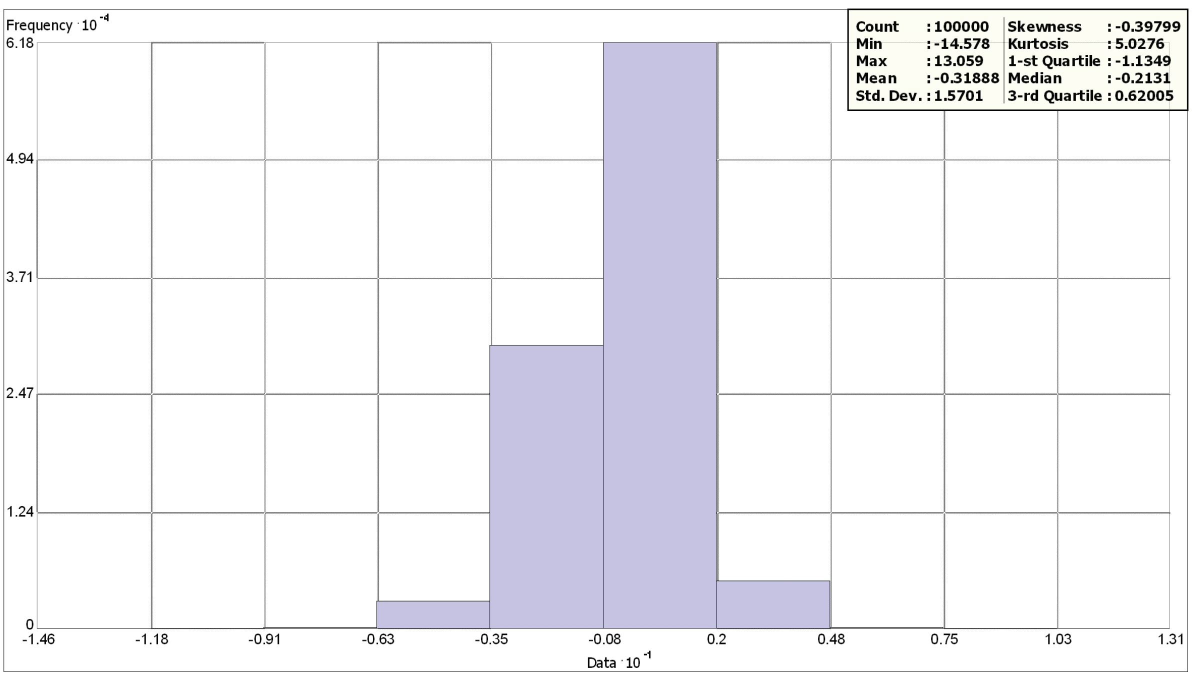

Figure 30. Histogram of the differences between select NED 1/9 arc-second topographic DEM data points and the Santa Monica NAVD 88 DEM.

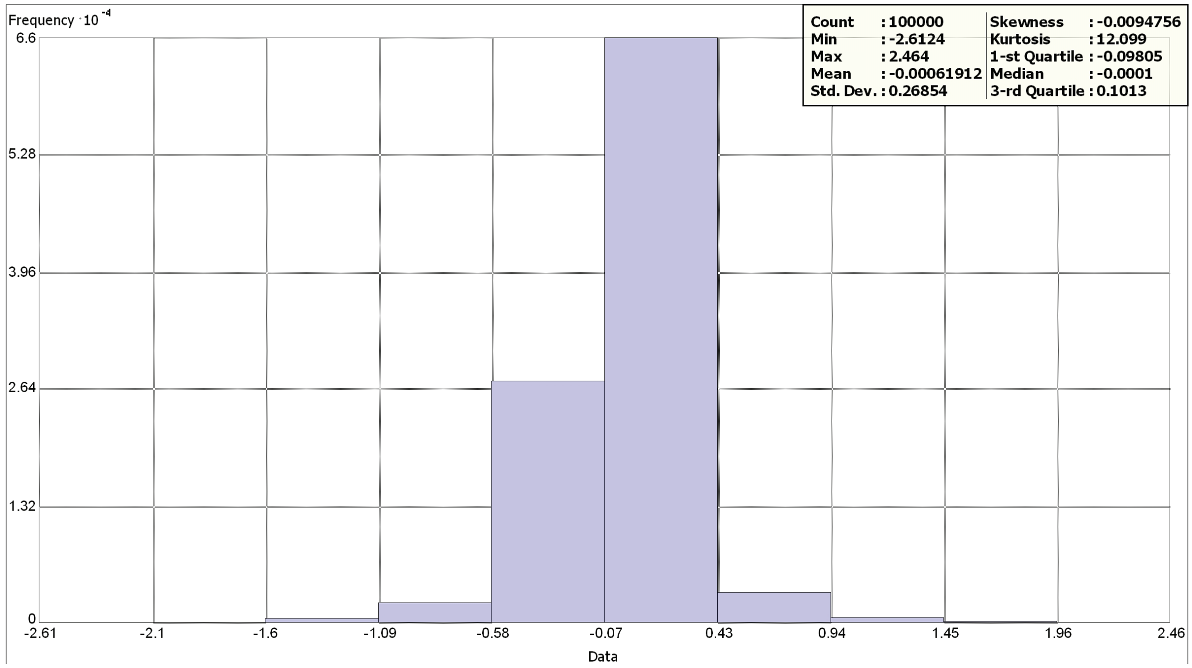

Figure 31. Histogram of the differences between select 2006 CSC topographic lidar data points and the Santa Monica NAVD 88 DEM.

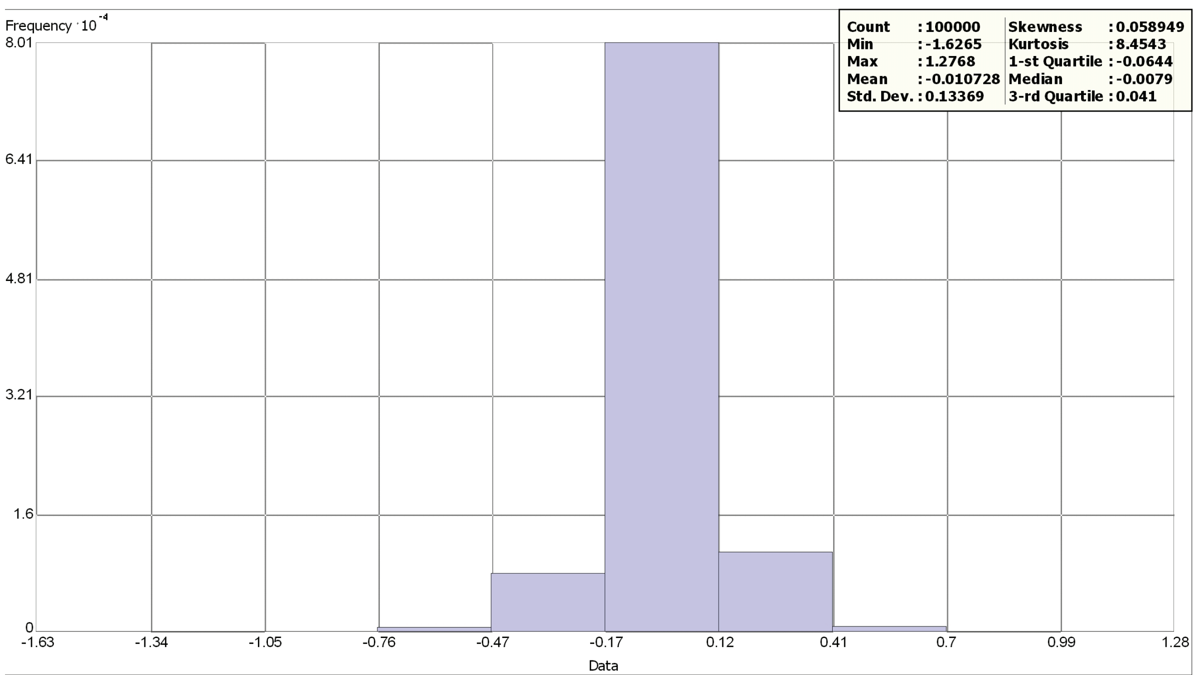

Figure 32. Histogram of the differences between select USACE hydrographic survey data points and the Santa Monica NAVD 88 DEM.

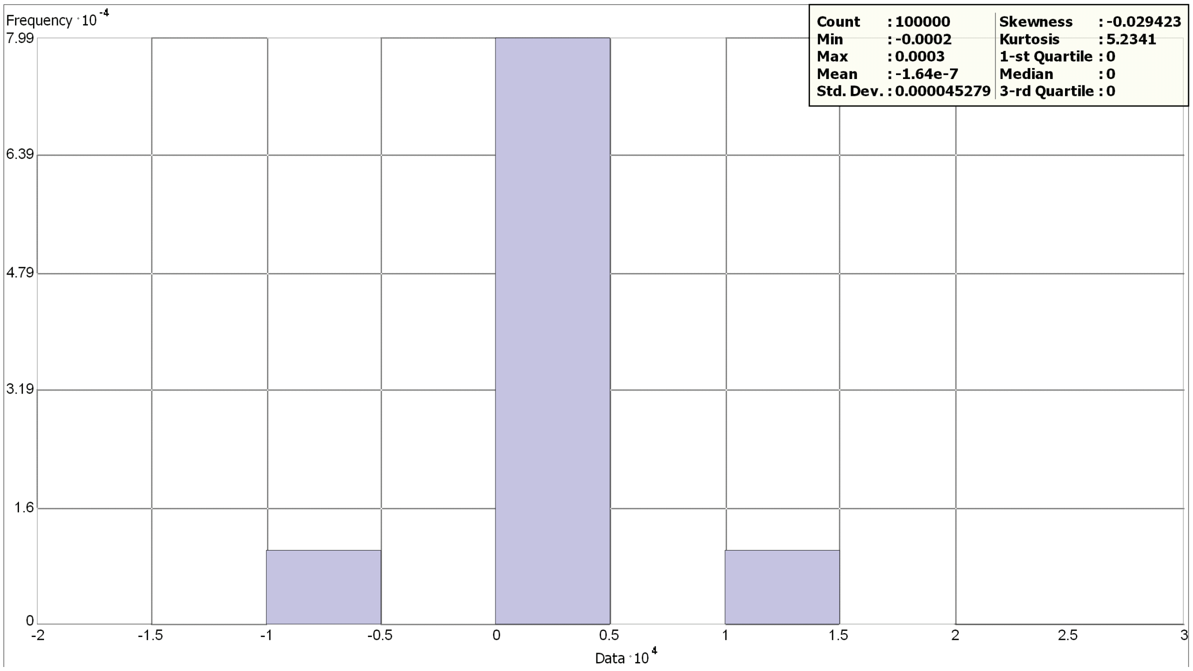

Figure 33. Histogram of the differences between select NGDC multibeam swath sonar survey data points and the Santa Monica NAVD 88 DEM.

4. Summary and Conclusions

Two integrated bathymetric–topographic digital elevation models of the Santa Monica, California region, with cell sizes of 1/3 arc-second, were developed for the Pacific Marine Environmental Laboratory (PMEL), NOAA Center for Tsunami Research. The best available digital data from U.S. federal, state, local, and academic agencies were obtained by NGDC, shifted to common horizontal and vertical datums, and evaluated and edited before DEM generation. The data were quality checked, processed and gridded using ESRI *ArcGIS*, ESRI *ArcGIS World Imagery 2-D*, *FME*, *Fledermaus*, *GMT*, *MB-System*, *QT Modeler*, and *VDatum* software.

Recommendations to improve the Santa Monica DEM, based on NGDC's research and analysis, are listed below:

- Conduct bathymetric surveys in the southwestern quarter of the 1/3 arc-second DEM region.
- Conduct additional bathymetric-topographic lidar surveys, particularly near Los Angeles and Long Beach Harbors.
- Process CSC and USACE lidar data to bare-earth.

5. Acknowledgments

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6. References

Lim, E., L.A. Taylor, B.W. Eakins, K.S. Carignan, R.R. Warnken, P.R. Medley. Digital Elevation Model of Portland, Maine: Procedures, Data Sources and Analysis. 2009. NOAA Technical Memoradum NESDIS NGDC-30. http://www.ngdc.noaa.gov/mgg/inundation/tigp/ngdc/data/portland_me/portland_me.pdf

Nautical Chart #18720 (ENC and RNC), 33rd Edition, 2009. Point Dume to Purisima Point. Scale 1:232,188. U.S. Department of Commerce, NOAA, National Ocean Service, Coast Survey.

Nautical Chart #18724 (RNC), 2nd Edition, 2009. Port Hueneme. Scale 1:20,000 and 1:12,500. U.S. Department of Commerce, NOAA, National Ocean Service, Coast Survey.

Nautical Chart #18725 (ENC and RNC), 29th Edition, 2009. Port Hueneme to Santa Barbara. Scale 1:50,000; 1:20,000; and, 1:12,500. U.S. Department of Commerce, NOAA, National Ocean Service, Coast Survey.

Nautical Chart #18740 (ENC), 12th Edition, 2009. San Diego to Santa Rosa Island. Scale 1:234,270. U.S. Department of Commerce, NOAA, National Ocean Service, Coast Survey.

Nautical Chart #18744 (RNC), 32nd Edition, 2009. Santa Monica Bay. Scale 1:40,000 and 1:10,000. U.S. Department of Commerce, NOAA, National Ocean Service, Coast Survey.

Nautical Chart #18746 (ENC and RNC), 37th Edition, 2009. San Pedro Channel. Scale 1:80,000 and 1:20,000. U.S. Department of Commerce, NOAA, National Ocean Service, Coast Survey.

Nautical Chart #18748 (RNC), 1st Edition, 2009. El Segundo and Approaches. Scale 1:15,000. U.S. Department of Commerce, NOAA, National Ocean Service, Coast Survey.

Nautical Chart #18749 (ENC and RNC), 42th Edition, 2009. San Pedro Bay. Scale 1:20,000 and 1:15,000. U.S. Department of Commerce, NOAA, National Ocean Service, Coast Survey.

Nautical Chart #18751 (ENC and RNC), 46th Edition, 2009. Los Angeles and Long Beach Harbors. Scale 1:12,000. U.S. Department of Commerce, NOAA, National Ocean Service, Coast Survey.

Nautical Chart #18756 (ENC and RNC), 8th Edition, 2009. Santa Barbara Island. Scale 1:20,000. U.S. Department of Commerce, NOAA, National Ocean Service, Coast Survey.

Nautical Chart #18757 (RNC), 11th Edition, 2009. Santa Catalina Island. Scale 1:40,000 and 1:10,000. U.S. Department of Commerce, NOAA, National Ocean Service, Coast Survey.

Nautical Chart #18762 (ENC and RNC), 15th Edition, 2009. San Clemente Island. Scale 1:40,000. U.S. Department of Commerce, NOAA, National Ocean Service, Coast Survey.

Nautical Chart #18763 (RNC), 10th Edition, 2009. San Clemente Island Northern Part. Scale 1:20,000 and 1:5,000. U.S. Department of Commerce, NOAA, National Ocean Service, Coast Survey.

Nautical Chart #18764 (ENC), 3rd Edition, 2007. San Clemente Island Pyramid Cove and Approaches. Scale 1:15,000. U.S. Department of Commerce, NOAA, National Ocean Service, Coast Survey.

Nautical Chart #18774 (RNC), 11th Edition, 2009. Gulf of Santa Catalina. Scale 1:100,000 and 1:15,000. U.S. Department of Commerce, NOAA, National Ocean Service, Coast Survey.

7. Data Processing Software

ArcGIS v. 9.3.1 – developed and licensed by ESRI, Redlands, California, http://www.esri.com/

ESRI World Imagery (ESRI_Imagery_World_2D) – ESRI ArcGIS Resource Centers http://resources.arcgis.com/

FME 2009 GB – Feature Manipulation Engine, developed and licensed by Safe Software, Vancouver, BC, Canada, http://www.safe.com/ .

Fledermaus v. 6.7.0 and 7.0.0 – developed and licensed by Interactive Visualization Systems (IVS 3D), Fredericton, New Brunswick, Canada, http://www.ivs3d.com/products/fledermaus/

GEODAS v. 5 – Geophysical Data System, free software developed and maintained by Dan Metzger, NOAA National Geophysical Data Center, http://www.ngdc.noaa.gov/mgg/geodas/

GMT v. 4.3.4 – Generic Mapping Tools, free software developed and maintained by Paul Wessel and Walter Smith, funded by the National Science Foundation, http://gmt.soest.hawaii.edu/

MB-System v. 5.1.0 – free software developed and maintained by David W. Caress and Dale N. Chayes, funded by the National Science Foundation, http://www.ldeo.columbia.edu/res/pi/MB-System/

Quick Terrain Modeler v. 7.0.0 – LiDAR processing software developed by John Hopkins University's Applied Physics Laboratory (APL) and maintained and licensed by Applied Imagery, http://www.appliedimagery.com/

VDatum Transformation Tool, California - Southern California from Morro Bay south to the US-Mexico border, v. 01 – developed and maintained by NOAA's National Geodetic Survey (NGS), Office of Coast Survey (OCS), and Center for Operational Oceanographic Products and Services (CO-OPS), http://vdatum.noaa.gov/